Master's thesis

NTNU
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The Beginning of the End

A Digital Planning of P&A Operations

Master's thesis in Petroleum Engineering
Supervisor: Behzad Elahifar
Co-supervisor: Bjørn Brechan

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ACKNOWLEDGMENTS

This thesis is a product of the course “TPG4920 Petroleum Engineering, Master’s Thesis” at the Department of Petroleum Engineering and Applied Geophysics, of the Norwegian University of Science and Technology in Trondheim, Norway.

I would like to invest this opportunity to thank several people who aided me intellectually and emotionally to successfully fulfill my work on this thesis.

First of all, I would like to thank my supervisor, Dr. Behzad Elahifar for his continuous support and follow up. I really appreciate all the positive vibes you used to spread in every meeting we had. In fact, this boosted my self-confidence and gave me a great motive to continue my work on the thesis. Thank you for always having the time to guide me through this thesis.

Second, I would like to sincerely thank my co-supervisor, Dr. Bjørn Astor Brechan, for suggesting such an interesting topic. I truly discovered the worth of this topic and the bright future it holds only after I started working with it. Thank you for always being there whenever needed, and above all thank you for our nice chats in which you continuously encouraged me and made me more familiar with the topic. Your guidance during the work with this thesis is highly appreciated.

I would also like to thank my family, who gave me this opportunity to come to Norway and pursue my master’s degree: *a dream I always wanted to achieve*. Mom & Dad thank you for your continuous encouragement and moral support you used to boost me with whenever I was feeling down.

Last but not least, I would like to thank my friend Philippe Chehade who supported me all the way through and gave me a valuable feedback on my thesis. Thank you for always being there when needed and for never failing to make me smile whenever I was disappointed! I would also like to thank my flat mate and friend Lay Trivedi who made my living experience in Norway a special and an unforgettable one. Thank you for all the support, late night talks, midnight snacks and for all the valuable memories you printed in my life.

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“Everything is theoretically impossible, until it is done.”

Robert A. Heinlein

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ABSTRACT

As it is commonly known, well abandonment operations can be very time consuming and expensive. Such operations may have a cost impact equivalent to the expense of the original drilling operation. Therefore, establishing cost efficient P&A strategies and technologies is a must knowing that the world will soon be facing a massive number of wells to plug.

Successful P&A operations depends on several factors such as casing conditions, cement status behind the casing, well barriers etc. It also involves different types of plugging material, plug placement techniques, cement evaluation tools, vessels, and drilling rigs. In return, this means that there exist several areas in any P&A operation that can be targeted and studied in order to favor cost reductions. However, one of the major obstacles faced today is the abandonment of old wells, implying significant costs to the industry. Why is that? At the time when old wells were planned, drilled, constructed, and set to production, it was not common to think about setting a plan for P&A design for the well. As a result, many challenges popped up such as lost or unavailable well information, inaccessible well logs and schematic diagrams. These challenges rendered the P&A operation a time consuming and expensive one. Therefore, and starting from this point, came the importance of early well planning in all disciplines and aspects. Dale Carnegie once said: "an hour of planning can save you 10 hours of doing"; planning is one of the most essential steps in any work conducted. Today, the oil and gas industry is in need of a digital system that can effectively plan all well activities, that too including P&A operations.

In its first chapters, this thesis provides insights about the process of plugging and abandonment of a well starting from the regulations and rules governing it reaching to several techniques involved in it. It will then discuss digitalization, its importance, and its history in P&A operations; to finally introduce a digital planning P&A software capable of making P&A operations simple, effective, less time consuming and above all less expensive. The framework of the software and what it is supposed to do are presented within the thesis, but the development method for the software requires further elaboration. The digital software presented is an underdeveloped prototype and requires more time, support, and feed (in terms of real-life data). Once fully operational, this software will be a "state of the art" rendering rig operations safer, less time consuming and more cost-effective.

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SAMMENDRAG

Som det er kjent, kan operasjoner for å plugge og forlate brønner være svært tidkrevende og kostbare. Slike operasjoner kan ha en kostnads tilsvarende den opprinnelige boreoperasjonen. Å etablere kostnadseffektive P & A-strategier og teknologier er derfor et must når man vet at industrien snart vil møte et massivt antall brønner å plugge.

P&A-operasjoner er avhengig av flere faktorer, for eksempel tilstand til rør, sementstatus bak foringsrøret, brønnbarrierer etc. Det involverer også forskjellige typer pluggmateriale, pluggplasseringsteknikker, sementevalueringsverktøy, fartøy og borerigger. Til gjengjeld betyr dette at det finnes flere områder i enhver P & A-operasjon som kan målrettes og studeres for å favorisere kostnadsreduksjoner. En av de største hindringene i dag er imidlertid plugging av gamle brønner, noe som medfører betydelige kostnader for industrien. Hvorfor? Før i tiden ble brønner planlagt, boret, konstruert og satt i produksjon, var det ikke fokus på P&A-design. Som et resultat dukket det opp mange utfordringer som tapt eller utilgjengelig brønninformasjon, utilgjengelige brønnlogger og skjematiske diagrammer. Disse utfordringene gjorde P & A-operasjoner tidkrevende og kostbar. Derfor, og med utgangspunkt i dette punktet, kom viktigheten av tidlig brønnplanlegging i alle fagområder og aspekter. Dale Carnegie sa en gang: "en times planlegging kan spare deg for 10 timers arbeid"; planlegging er et av de viktigste trinnene i ethvert utført arbeid. I dag har olje- og gassindustrien behov for et digitalt system som effektivt kan planlegge alle brønnaktiviteter også inkludert P & A-operasjoner.

I de første kapitlene gir denne oppgaven innsikt i prosessen med å plugge og forlate en brønn, med utgangspunkt i regelverket og reglene som styrer den, og presenterer flere teknikker som er involvert i den. Så diskuteres digitalisering, betydning og historie i P&A-operasjoner; til slutt introduseres en prototype for enklere P & A-operasjoner, effektive, mindre tidkrevende og fremfor alt billigere. P&A rammeverket for programvaren og hva det skal gjøre presenteres innenfor oppgaven, men utviklingsmetoden for programvaren krever nærmere utdyping. Den digitale programvaren som presenteres er en underutviklet prototype og krever mer tid, støtte og input (når det gjelder virkelige data). Når denne programvaren er i full drift, vil den være en "moderne metode" som kan gjør riggoperasjoner tryggere, mindre tidkrevende og mer kostnadseffektive.

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CHAPTER 1: INTRODUCTION

In the last decade, the industries of the world started to undergo a transition, a transition that began as a dream, grew up to an idea and then started to manifest itself as a reality. This transition is the automation and digitalization of everything man once used which made life easier and more efficient. Like many other industries, the oil & gas industry got the chance to be involved in this transition, yet it is still one of the industries that is lagging behind where it has always resorted to outdated conventional methods instead of thinking out of the box and developing efficient techniques to solve ongoing problems. According to Forbes contributor, Martha Aviles from Drilling info, ever since the WTI was over 100$/barrel in 2014 and the oil economics were skyrocketing, not a single effort was put in order to improve efficiencies. Furthermore, Aviles (2015) stated that: “In the oil and gas industry, there was no real precedent for updating products and tools when compared to other industries where the pace of technology adoption is widespread”. Back then, the statement by Aviles can be justified by the fact that the industry was in good shape and billions have been made by just depending on “traditional” methods. Hence, there was no incentive that would push any oil and gas company to investment money in the R&D department for the sake of enhancing efficiencies and increasing profit. However, many things changed from 2014 up till April 20th,2020, where the oil and gas prices dropped drastically to an extent that the WTI price fell from 17.85$ at the start of the trading day to negative 37.63$ by the close. This incident reminds us of the volatility of this industry and urges the industry to create/implement new techniques that would render more efficient and less costly methods. Thus, projects to establish and implement digitalization and automation were initiated. The segment this thesis focuses on, is the plugging and abandonment of “old” wells. These operations secure wells by installing the required well barriers (as defined by NORSOK D-010).

P&A operations are usually less thought off in the early planning of drilling projects. In fact, many wells were designed without taking into consideration how they should be plugged. Today, a high number of production wells have come to the end of their service and are scheduled to be permanently plugged. this is not to mention also that many wells are to be abandoned due to the covid-19 world pandemic. According to Silvio Marcacci (2020), a contributor at Forbes, the number of abandoned wells increased 12% across the U.S. since the fracking boom began in 2008, and that number will likely surge as bankruptcies rise. Marcacci (2020) also added that BP recently declared peak oil may have occurred in 2019, with demand never to recover, meaning this wave of bankruptcies could push tens of thousands of now-idled wells to become permanently abandoned wells. This confirms the fact that the world is currently facing what is known as a "Plug Wave" where the number of wells to be abandoned has already ballooned way beyond what manpower and state budgets can handle. Many experts agreed that this number is on the verge of becoming a problem. "The numbers are staggering," Greg Rogers, a senior advisor at the financial think tank Carbon Tracker. "There's no war chest at the corporate level or the state level to pay for that" (Pontecorvo, 2020).

Along with covid-19 world pandemic, comes the impact of environmentalists that are severely fighting the oil and gas industry demanding the cease of oil and gas production. Kristian Elster, a Norwegian journalist at NRK, published an article on June 3rd of this year (2021) under the title: "*Fire sjokk på ti dager: – Et vendepunkt for oljeindustrien*" which translates to "*Four shocks in ten days: - A turning point for the oil industry*". In his article Elster (2021) discusses four major events that happened within 10 days that could "flip the table" on the petroleum industry. Several well-known oil and gas operators such as Shell (Netherlands), ExxonMobil, and Chevron are now forced/sentenced to cut on their carbon emissions and divert their focus/investments to renewable energies just like what the French oil giant "Total" did on the 28th of May, 2021; where it presented a new strategy (and a new logo under the name of "Total Energies") to make the company more climate-friendly towards the year 2050.

It is assumed that if new field investments were stopped, the world oil production will drop by 4-6 percent a year. And if investment in fields that are already in production is ceased, then the world oil production will fall by 15–20 per cent a year (as cited in Elster,2021). In return, all these "environmental" on-going happenings will soon have a great impact on the oil and gas industry which will trigger the plugging and abandoning of several oil wells. Therefore, it is now the time to render P&A operations efficient and less costly by developing the technology needed.

This master's thesis comprises two major parts. The first part covers a general overview of P&A, fundamental acts, regulations, and requirements governing this operation (minimum standard/quality), including the operational challenges operators often face. In the second part, the thesis proposes a new technique for the digital planning of plugging and abandonment operations by using a digital framework that aims to diminish the planning time without increasing project manhours. The thesis introduces a digital prototype capable of planning some activities (not all due to time limitations) involved in P&A operations along with some tangible examples. It also sheds light on possible challenges that can jeopardize the progress in building up this digital software. Last but not least, the thesis proposes some future developments that can render the developed prototype a "state-of-the-art".

CHAPTER 2: INTRODUCTION TO PLUGGING AND ABANDONMENT

2.1 WHAT IS P&A?

Most oil and gas fields are designed to have a life cycle that stretches over decades. Five main stages can be noteworthy in the life of any oil and gas field which are: exploration, appraisal, development, production, and abandonment.

The abandonment phase, known as "plugging & abandonment", is the last stage in the life cycle of a drilled well. Normally, it is the stage when economically recoverable reserves have been extracted and the operating income generated from production is lower than the operating expenses; thus, rendering the well economically unattractive.

Plugging and Abandonment can be described as the process by which a well is shut permanently with the aid of plugging materials and abandonment strategies, which in turn isolate each and every permeable hydrocarbon zone and water zones of different pressure regimes from each other and from the seabed as well. P&A operations are considered to be an important part of decommissioning, since inappropriately sealed zones could cause a major threat to the environment and . In order to ensure full well integrity (defined in section 3.2.1), there are a set of rules and regulations that have to be followed. It is important to highlight the fact that P&A requirements might vary from one country to another, but the main goal which is to ensure that the well is sealed and isolated in an eternal perspective remains the same. This thesis will be exclusively focusing on the rules and regulations set by the Norwegian Petroleum Safety Authority (PSA) and will be tackled later on in section 3.1.

NORSOK D-010 rev.4 is the standard that defines the minimum functional and performance-oriented requirements and guidelines for well design, planning, and implementation of safe well operations. In chapter 9 of this standard, plugging was defined as the "operation of securing a well by installing the required well barriers" and what was meant by well barriers is the set of elements that prevent pressure buildup or crossflow in the well and its surroundings. Furthermore, this standard split P&A into two groups: temporary and permanently abandoned wells. A temporary abandoned well is a well that shall be possible to re-access safely at a later stage during the planned duration of abandonment. Whereas a permanent abandoned well is a well that will never be used or re-entered again, and thus shall be plugged with an eternal perspective considering all foreseeable geological and chemical processes and loads that might occur in the well after its barriers were established. Permanent and temporary abandoned wells are discussed further in section 3.4.

2.2 P&A AND COVID-19 WORLD PANDEMIC

The covid-19 pandemic had a significant impact on the oil and gas industry. Oil prices witnessed a severe negative drop, and many oil companies were threatened by an increased potential of bankruptcy. This economic shock encountered by the energy sector pushed many companies to put their projects on hold and by that many wells had to be plugged and abandoned. According to E&E news reporter Heather Richards (2020): “The New Mexico State Land Office created an emergency rule to allow shut-ins of wells; Oklahoma's Corporation Commission voted for a similar allowance. As many leases require continuous production, the state will also allow operators to stop production without violating leases.”

This pandemic caused many oil wells to be abandoned by companies financially disrupted amid low energy prices and scarce demand brought on by the pandemic. In addition to that, many wells were “orphaned” meaning that the company responsible for that well could not afford any further activity on site and left the well unplugged. Hence, this pushed several states in the United States to use Covid-19 aid money to plug these wells for they might impose hazardous risks on the wellbeing of both humans and the surrounding environment. According to AP news, “North Dakota wants to use $33.1 million in federal coronavirus aid to plug “orphaned” oil wells…... The North Dakota Emergency Commission, headed by Republican Gov. Doug Burgum, approved the funding. The commission in total approved $524 million, or 42% of the $1.25 billion given to the state as part of the federal stimulus package approved in March.” (MacPherson, 2020).

On the other hand, and apart from the economic crisis Covid-19 had caused, some wells had to be temporary plugged and abandoned due to the fact that social distancing cannot be applicable while being on the rig. This was also a challenge faced by several companies and therefore was another reason behind the plugging and abandonment of some wells.

As it is clearly noticed, today the world is facing a huge “plug wave” as a result of the pandemic and decreased oil price; hence establishing an affordable P&A operation is now a must because many companies are not willing to pay much on decommissioning projects especially during these crises. And perhaps this can only be accomplished by the digitalization and automation of this process.

CHAPTER 3: PLUGGING & ABANDONMENT REGULATIONS, REQUIREMENTS AND DEFINITIONS

3.1 REGULATIONS, ACTS AND RULES

An important standard followed by many industry professionals and companies is NORSOK D-010. This is a set of guidelines that tackle well integrity issues throughout the entire life cycle of the well starting from its construction reaching its abandonment. This standard was first issued in mid-2004 and has been frequently updated depending on the experience acquired/needed. The latest revision (rev.5) was published in January 2021, and it will serve as the basis for this master's thesis. The primary aim of the standard is to:

- Prevent hydrocarbon movement between different layers of the formation (layer crossflow)
- Prevent hydrocarbon leakage to the surface.
- Prevent pressure breakdown of the formation.
- Prevent the contamination of freshwater aquifer.

It is important to highlight the fact that NORSOK D-010 guideline solely serves as a recommendation provider to execute the requirements of the regulations issued by the Norwegian Petroleum Safety Authority (PSA). PSA *is a government supervisory and administrative agency with regulatory responsibility for safety, the working environment, emergency preparedness and security in the petroleum sector* (Norway,2021). In other words, this standard only describes the minimum requirements to maintain well integrity through well design, planning, and execution of well operations in Norway. Hence, it is the operating company's responsibility to plan and design the well operation in a way that secures the well integrity throughout the entire life cycle of the well and check whether the design matches with the minimum requirements of the NORSOK standard. This in turn justifies the reason behind why some companies like Equinor and ConocoPhillips have developed their own internal requirements which can be more stringent than NORSOK D-010 standards at some point.

Hence, when it comes to P&A operation execution, its crystal clear that there is a hierarchy that must be followed and on the top of this hierarchy comes the Norwegian Petroleum Act of 29 November 1996. In short, this act ensures that each and every petroleum activity carried on the NCS is managed properly and that all Norwegian interests are well protected. The figure below shows this hierarchy and how it is structured in Norway.

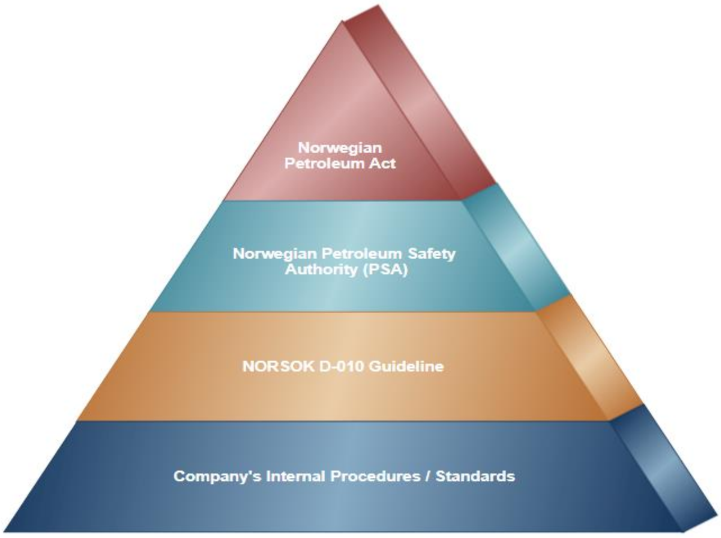


Figure 1: *Acts & Regulations hierarchy in Norway*

3.2 IMPORTANT TERMS AND DEFINITIONS

P&A operations are considered to be one of the most delicate operations conducted on the rig. P&A is not as easy as pouring cement into the wellbore and praying that the cement forms a proper seal. In fact, the operating company is (by law) responsible for conducting the P&A operation and ensuring that there are no leaks in the well. And even after the operation is done, if any leak happens on the long run, the company is held responsible to pay all the costs to clean and re-plug the well properly.

When it comes to P&A requirements two important terms stand out which are: well integrity and well barriers, hence it is vital to understand the definition of these two terms.

3.2.1 Well Integrity

Well Integrity is defined in NORSOK D-010 (2021) as: "application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well".

Torbergsen et al. (2012) simply defined well integrity as a condition of a well in an operation that has full functionality and two qualified well barrier envelopes. Any deviation from this state is considered to be a minor or major well integrity issue. Common integrity issues are often related to leaks in tubular or valves but can also be linked to reservoir issues such as loss of zonal control. Any factor that leads to a functional failure is a loss of well integrity.

At the abandonment stage, well integrity becomes more challenging especially if it was not considered during the planning and designing phase of the well. When the abandonment stage is reached, the well would have been already passed through many phases and in turn a huge number of information would have been collected and processed. However, sometimes vital information (such as pressure data) might be incomplete or maybe completely missing. Therefore, this might impose a big challenge on the risk management team on how to plan the abandoning of the well.

The main goal of planning well integrity is to pinpoint potential hazards that might occur at different stages during the well's lifecycle. Formation induced problems such as temperature, pressure, mobility of formation fluids can be the main reason behind integrity problems. In addition, integrity problems can be a result of operational induced problems, such as lack or poor maintenance of equipment, operating the well and equipment above the design limit, equipment failures, installation failures and failures linked to testing and verification (Vignes, 2011). The consequences of lost or reduced well integrity loss can cause equipment damage, personnel injuries, and environmental harm. This in turn can be costly and risky to repair. Well integrity losses can lead to blowouts or leakage, which is a concern in this context. Thus, it is important to handle well integrity issues carefully and perhaps take it more into account during the design and planning phase.

3.2.2 Well Barriers:

The primary use of well barriers is to avert any leakage, ensure complete and adequate isolation of mobile fluids, prevent leakage within the wellbore and unintentional flow from the seabed or surface. Well barriers must be established in every stage of the well's life cycle from drilling, testing, completion, production reaching plugging & abandonment.

According to NORSOK D-010, well barrier is portrayed as envelope of one or several dependent barrier elements preventing fluids or gases from flowing unintentionally from the formation into another formation or to surface.

Well barriers are basically established through the use of well barrier elements (WBEs). A well barrier element is a physical element which, in itself, does not prevent flow but in combination with other WBEs forms a well barrier envelope (NORSOK D-010, 2021). All WBEs used in plugging operations must be capable of enduring the load and environmental conditions in case they were exposed during the abandonment period; this can be ensured when some uncertainties are taken into account during the design and placement phase of the WBEs.

According to NTNU's TPG4215 course compendium (2017), these uncertainties are usually linked to:

- Surface volume control
- Contamination of fluids
- Pump efficiency
- Shrinkage of cement or plugging material
- Downhole placement techniques
- Casing centralization
- Minimum volumes required to mix homogenous slurry
- Support for heavy slurry
- WBE degradation over time

These specific uncertainties must be checked due to the fact that cement (slurry) is one of the essential materials used more often to establish the well barriers required for plugging purposes.

Furthermore, well barrier schematics (WBS) must be prepared for all activities in the well which also includes well abandonment. A WBS is principally a sketch/drawing that mainly shows both primary well barrier (in blue color) and secondary well barrier (in red color) which in turn must be completely independent of one another with no common WBE. It also contains more details such as a tabulated list of WBEs, tubulars and cement, well information and much more. A blank template of a WBS can be found in *Appendix 1*. It's important to note that, for permanently abandoned wells, having two well barriers (primary & secondary) is usually not sufficient. A blend of distinct well barriers must be considered such as an open to hole surface barrier and a barrier between separate reservoirs.

3.3 Well Barrier Requirements

Torbergsen et al. (2012) characterized the well barrier's performance by its:

- **Functionality:** what function will it perform (maintain overbalance, prevent blowout, detect a kick…), and within what time frame will this function be attained.
- **Reliability / Availability:** how reliable the barrier would be to perform the required functions under the ongoing operating conditions and within a limited time range (answer to this would be in terms of probability).
- **Survivability:** which basically depicts the ability of the barrier to withstand the stress under a specific demanding state.

The Norwegian Petroleum Safety Authority (PSA) distinguishes in many sections of its regulations between requirements that apply to barriers in general and barriers needed for securing the well. The general requirements are mainly found in sections §48 and §85, of the regulations which in turn also refers to some chapters of NORSOK D-010 standard. These two sections briefly state that:

- The barriers shall be designed such that well integrity is safeguarded, and the barrier's functions are maintained throughout the whole life cycle of the well.
- The barrier shall be designed such that its position and status can be verified at any time.
- Unintended well influx and outflow to the external environment must be prevented by at least two independent and tested/ qualified well barriers and in a way that does not affect any well activity.
- In the event of a barrier failure, all well activities must be ceased except the activities responsible for re-establishing the barrier.
- When plugging the wells, it shall be possible to cut and retrieve the casings without damaging the surroundings.

The requirements needed to secure the wells during P&A, can be found in section §88 of the regulations enforced by PSA (2018). These requirements affirm that:

- All wells shall be secured before they are abandoned so that well integrity is protected during the time they are abandoned. For subsea-completed wells, well integrity shall be checked if the plan is to abandon the wells for more than twelve months.
- Exploration wells started after 1.1.2014 shall not be temporarily abandoned beyond two years. In production wells abandoned after 1.1.2014, hydrocarbon-bearing zones shall be plugged and abandoned permanently within three years if the well is not continuously monitored.
- It shall be possible to check well integrity in the event of reconnection on temporarily abandoned wells.
- Abandonment of radioactive sources in the well shall not be planned. If the radioactive source cannot be removed, it shall be abandoned in a prudent manner.

3.4 Suspension vs. Temporary & Permanent Abandonment:

The main purpose behind plugging off a well is to cease production or the flow of reservoir fluids. The non-producing wells are categorized into 3:

- Suspension
- Temporary Abandonment
- Permanent Abandonment

Table-1 pinpoints the difference between these 3 categories.

Table 1: *A table projecting the difference between suspended, TA, & PA wells. (Retrieved from NORSOK D-010)*

Suspended Well	Temporarily Abandoned (TA) Well	Permanent Abandoned (PA) Well
• A well on which operations have been ceased. • Uncompleted well, temporarily abandoned but not permanently • Well control equipment is not retrieved back • Applies to wells under construction or intervention • Well barriers and WBE material(s) are required to have adequate integrity for the whole period of suspension (including contingency)	• An inactive well whose completion interval is isolated. • Should be used when an operator is holding a wellbore in expectation of future utilization (e.g., enhanced recovery project) • Shall be possible to re-access in a safe manner and resume operations during the planned duration of abandonment • Differentiated between monitored & unmonitored abandonment	• A well that will never be used or re-entered again • Must be plugged with an eternal perspective taking into consideration all foreseeable processes and loads it may be exposed to. • More details can be found in section 3.5.

This master thesis will be only considering the aspects of a permanent abandoned well.

3.5 PERMANENT ABANDONMENT:

A permanent well abandonment implies that the well will never be used or re-accessed. Hence the well must be plugged with an eternal perspective, accounting for all expected loads and conditions the well might encounter during the whole abandonment period. One of the most important concepts when permanently abandoning the well is to make sure that the permanent barriers seal the whole cross-section of the well including all annuli, both vertically and horizontally as shown in figure 2. In addition, these barriers shall also be set adjacent to low-permeable or impermeable formation with adequate formation integrity for the maximum anticipated pressure (NORSOK D-010 , 2021).

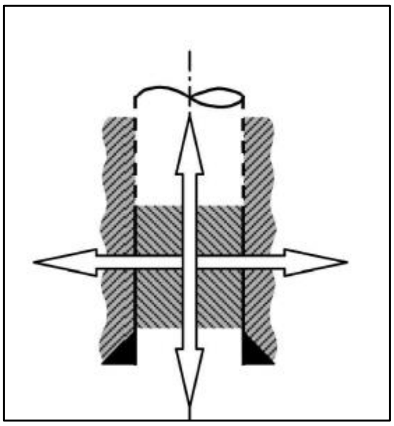


Figure 2: *Well barrier sealing in both directions (vertical & horizontal). Retrieved from NORSOK D-010*

NORSOK D-010 recommends (does not require) a set of properties for a permanent well barrier. These properties/ characteristics are:

- Non-shrinking
- Impermeable
- Able to endure mechanical loads/impact
- Provide long term integrity (eternal perspective)
- Resistant to different chemicals/ substances such as H_2S, CO_2 and hydrocarbons
- Not harmful to the steel tubulars' integrity
- Ensure bonding to steel

Following is a more detailed explanation about the requirements stated in Table 24[1] of NORSOK D-010 (2021). In order to prevent the flow of hydrocarbons and/or over pressurized

[1] EAC table 24 is a table in NORSOK D-010 that describes the acceptance criteria for cement plugs. It basically states the function, design, construction, and selection of cement plugs. In addition to other features such as the initial verification of cement plugs.

fluids through the wellbore, the barriers must be impermeable. In fact, this is the most essential characteristic where the whole purpose of setting a plug is to stop any flow between the wellbore and surrounding formation. However, fluid migration is a natural phenomenon that might also occur in a permanent barrier. Therefore, what is important in this case is the rate of fluid movement. A rule of thumb, as long as the fluid migration in the plug is equal or less than in the cap rock it should not be a problem. It is estimated that the permeability of a cap rock ranges between 0,001 -1 micro-Darcy (O.G. UK, 2012). Flow through the plug can be highly influenced by fluid injection, as increased pressure favors the decrease of the effective stress around pores and fractures, pushing them to open. Other factors such as thermal changes, rock movement, gas storage or CO_2 injection and mechanical stresses may also impose a great impact on the sealing barrier. Portland cement was and still is the mostly used plugging material. It has been significantly improved by the use of some additives such as retarders, accelerators, loss circulation material etc... What makes the Portland cement an attractive plugging material is that it is cheap, readily available, durable and has been widely tested on the NCS. Therefore, NORSOK bases its entire recommendations on cement being a barrier with a lot of advantages. According to NORSOK D-010, for the barrier to stay impermeable for eternity the required length of the cement plug is 100 m measured depth if the plug is set inside a casing and 50 m MD if a mechanical plug is used as a basis. In addition to that, it is also vital that the plug should extend a minimum of 50 m above any source of inflow or leakage point.

It is also required that the permanent barrier must be non-shrinking. Shrinkage after cement has settled favors the creation of micro channels in it, which in turn means that fluid flow between the barrier plug and the casing annulus is not blocked anymore. Shrinkage may occur during the solidification process (going from liquid to solid state) due to the chemical reactions taking place. Shrinkage may also be an outcome of aging.

One of the most essential requirements a permanent barrier must possess is long term integrity, which means that material (cement in our case) must preserve its sealing properties even after being exposed to downhole conditions for a long period of time. It is usually challenging to assess the long-term performance; therefore, ageing tests were always conducted to estimate the durability of the cement placed downhole.

It is also essential to ensure that the placed cement bonds with the steel casing and the exposed formation. If bonding was not established, there is a high probability that a micro-annulus will be formed serving as a potential leakage pathway for fluids.

NORSOK D-010 (2021), lists in section 10.6.3 several additional requirements and guidelines for permanent well barriers such as those projected in the table below:

***Table 2**: Additional EAC requirements. (Retrieved from NORSOK D-010- Table 27)*

Element Name	Additional features, requirements, and guidelines
Casing	Steel tubulars WBE shall be supported by cement or alternative materials.
Annulus Cement	Cement in the liner lap or in tubing annulus may be accepted as a permanent WBE when the liner is centralized in the overlap section. The annulus cement in the liner lap shall be logged.

In addition, NORSOK D-010 (2021) conditions that: “When completion tubulars are left in the well and WBE are installed in the tubing and annulus, the position and integrity of these shall be verified:

- The annulus cement between the casing and tubing shall be verified by pressure testing.
- The cement plug (inside tubing) shall be tagged, and pressure tested.”

More requirements regarding internal and external well barrier elements, and their reduced length assessment can be found from section 10.6.3.2 →10.6.3.6. The external WBE is usually the casing cement and the internal WBE is normally the cement plug.

3.5.1 Number of well barriers:

What is commonly agreed on in the industry is that at least two independent barriers must be set in place at all times. These two independent barriers are known as the primary and secondary barrier. The primary well barrier is basically the first barrier that will be facing any potential source of inflow or leakage. Its main goal is to isolate the reservoir from the wellbore in order to prevent fluid migration from the reservoir into shallower permeable formations or to the surface. The secondary well barrier also has the same function as the primary one (isolation of zones in the wellbore to prevent any flow potential) and serves as backup to the primary WB. Cables and control lines should not be considered as a part of permanent barriers because they may be a potential path for leakage.

NORSOK D-010 (2021), considers three well barriers which shall be a result of well plugging activities. It is important to note that one barrier was omitted from the new version of NORSOK standards which was the “cross-flow barrier”. These 3 barriers are:

- **Primary well barrier:** To isolate a source of inflow, formation with normal pressure or over-pressured formation from surface/seabed.
- **Secondary well barrier:** Back-up to the primary well barrier against a source of inflow.
- **Open hole to surface plug:** Prevent access to well after casing(s) are cut and retrieved and contain environmentally harmful fluids. The exposed formation can be over pressured with no source of inflow. No hydrocarbons present.

On a side note, NORSOK D-010 states that multiple reservoirs/ perforations located within the same pressure regime can be regarded as one reservoir for which a primary and secondary well barrier shall be installed as depicted in Figure 3 . In addition, the standard permits a well barrier to function as a shared well barrier for more than one wellbore.

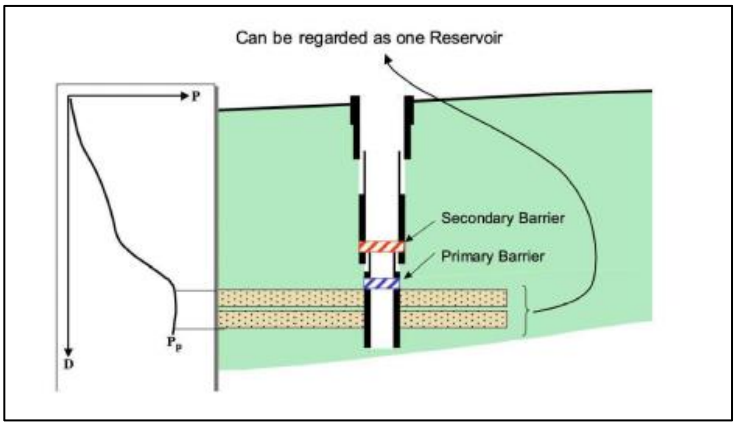


Figure 3: *Multiple Reservoirs (NORSOK 2021, p. 97)*

3.5.2 Length of the well barrier:

One of the most important requirements a well barrier must possess is that it must have sufficient strength and shall extend across the whole cross-section of the well, including all annuli and sealing both vertically and horizontally as shown in Figure 1. As for the length of the well barrier (cement plug), it is usually more based on experience and common sense rather than on a proven scientific study. NORSOK D-010 specifies the minimum length requirements which in turn are outlined in the table below:

Table 3: *NORSOK D-010 minimum requirements for cement barrier's length*

Cased hole cement plugs	Open hole cement plugs	Open hole to surface plug
100 m MD	100 m MD with a minimum of 50 m MD above any source of leakage or inflow	100 m MD
50 m MD if placed on a cement /mechanical plug as a foundation If the qualified annular barrier length is 30 m and set on a mechanical/ cement plug as fundament the plug may be 30 m.	A plug-in transition from open hole to casing should cover at least 50 m MD above and below the casing shoe	50 m MD if placed on a mechanical plug

A summary of requirements for barrier length using different standards can be found in Appendix 3.

3.5.3 Barrier position requirements:

The position requirements discussed in this section are solely based on the NORSOK D-010 standards, which in turn specifies that the base of the well barriers shall be positioned at a depth where formation integrity is higher than potential pressure below and this condition applies for both primary and secondary barriers. In other words, the well barrier(s) must be able to withstand the maximum potential internal pressure below or at the base of the plug.

The formation integrity pressure is usually obtained by the means of a formation integrity test (FIT) also known as pressure integrity test (PIT). According to NORSOK D-010 (2021), the formation integrity pressure is the pressure representing the strength of the formation (FBP), which can be either FIT/PIT or the interval between fracture breakdown pressure (FBP) and fracture closure pressure (FCP).

The figure below shows an idealized pressure-volume plot for all applied pressure integrity tests such as FIT, LOT & XLOT/ELOT.

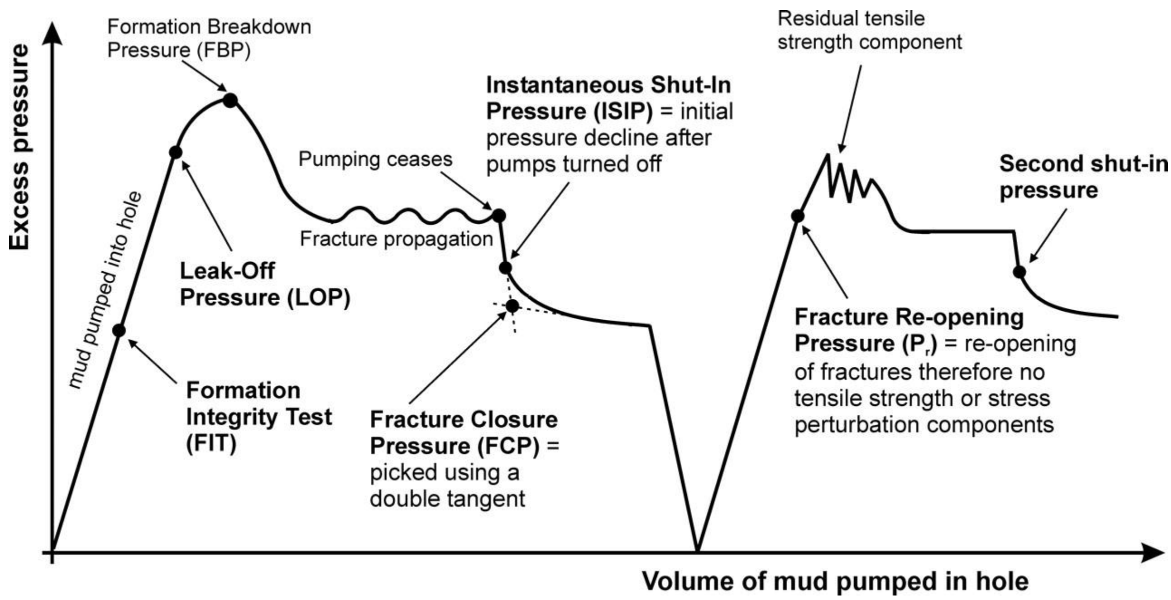


Figure 4: *Idealized Pressure-Volume plot for all PITs. Source: Meta Innovation Technology 2020*

More details on formation integrity tests, and the process of determining the depth at which the base of the barriers shall be set can be found in *Appendix 2.*

3.5.4 How are barriers established?

According to NTNU’s TPG4215 course compendium (2017), the steps to form the first barrier during the P&A phase in a producing well are the following: (refer to figure 5)

1. A bridge plug or cement retainer is installed by using WL to avert the flow of hydrocarbons inside the well (shown in illustration #2). Once this plug is installed and verified, the tubing would be punched, this is a benign perforation to avoid damage to the casing outside the tubing. After that, the circulation of fluids in the tubing and A-annulus by either seawater or brine will take place. In order for the well to have barriers in place when removing the XT, a shallow plug would be installed.

2. The casing is then cut, as shown in illustration #3. This step is also known as casing or section milling.

3. A drill pipe string is run closed to or connected to the deep-set plug. The bottom part of a plug is a sub that can be replaced. Usually, in a situation like this, the stinger at the end of the DP can unlock a port at the bottom of the plug through which cement can be squeezed. In this

way, the exposed perforations can be (partly) blocked and the fluid will go the way of least resistance. A plug with such a bottom sub is called a cement retainer.

4. Finally, a balanced cement plug must be set. Then, the primary barrier elements are installed inside the well; formation, casing cement, casing, barrier cement plug, as shown in illustration #5.

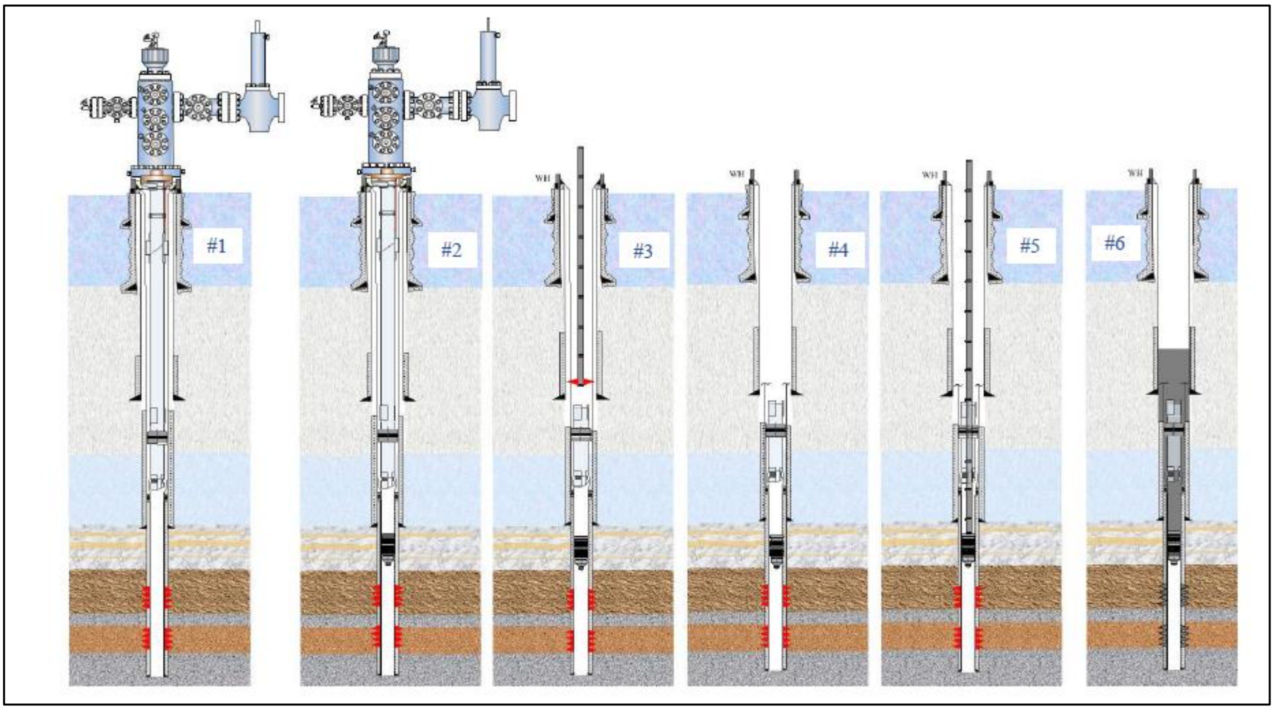


Figure 5: *P&A sequence to establish a barrier. (TPG4215 NTNU compendium,2017)*

3.5.5 Barrier Verification:

All permanent barriers must be verified to ensure that they have been placed at the required depth and that they possess the required sealing capabilities. In addition, they must be verified in order to guarantee that they can withstand potential differential pressure. How the plug/ barrier is tested is fully dependent on the plug type.

The initial plug verification steps can be found in EAC table 24- Cement plug (NORSOK, 2021). According to this table:

1. The strength development of the cement slurry should be verified through observation of surface samples from the mixing cured on-site in representative temperature.
2. The plug installation must be documented through evaluation of cement job execution taking into consideration the volume of pumped cement, returns during cementation, and estimated hole size.
3. If the plug type was an open hole one, then it shall be verified by tagging.

4. If the plug type was a cased hole one, then it shall be verified by tagging and pressure testing. Pressure test shall:
   - be approximately 1000 psi above estimated leak-off pressure (LOT) below casing/ potential leak path or approximately 500 psi for surface casing plugs
   - not exceed the casing pressure test and the casing burst rating corrected for casing wear.

   Some important notes:
   - If the cement plug is set on a pressure tested foundation, a pressure test is not required. It shall be verified by tagging.
   - Tagging can be omitted if some conditions were met. These conditions can be found on page 211 in NORSOK D-010 2021 standards.
5. If the plug type was an open hole to surface plug it shall be verified by tagging. If the open hole to surface plug is set on a verified mechanical fundament, tagging may be omitted.

A summary of requirements for barrier verification using different standards can be found in *Appendix 3.*

3.6 SLOT RECOVERY:

Slot recovery, also known as sidetracking, is a cost-effective process that aims to enhance production. Prior to sidetracking, the bottom of the original wellbore must be permanently abandoned and then a new slot is opened in the upper section of the well to sidetrack favoring the reach of new targets (Figure 6) . According to Bailey et. al (1998), the slot recovery/ sidetracking process can cut the cost in half, and it is way cheaper than drilling a new well instead. In addition, this process favors the reuse of the top infrastructure to drill multiple new wells which makes it economically attractive.

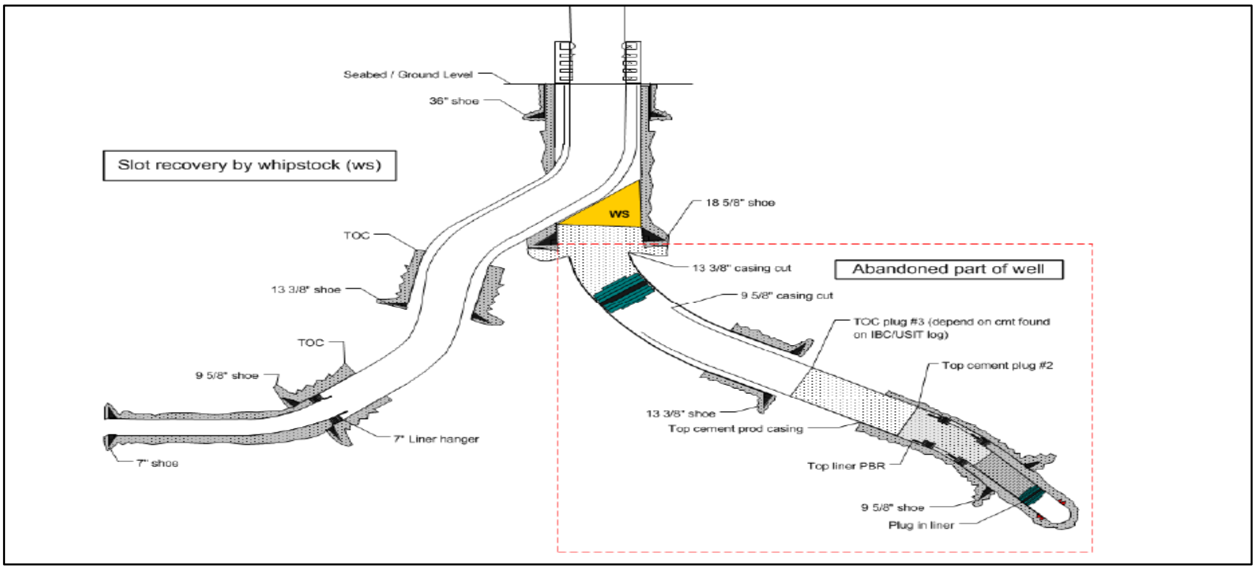


Figure 6: Slot Recovery Example. (Source: NTNU- TPG4215 Compendium,2017)

CHAPTER 4: P&A OPERATIONAL PROCEDURE

Each well scenario has a variety of uncertainties and factors that need to be individually assessed. Therefore, standardizing a plugging and abandonment operation is quite uncommon and it is usually a twisted challenging task. Neither engineers working within this domain nor written literature can provide a straightforward description of how this process can be carried. One of the key aspects that aids reaching a well-defined P&A operation procedure is the accessibility of reliable real-life data tackling the entire phases and conditions a well can pass through during its entire lifecycle, for example well completion and design, well performance, interventions performed, cement status, number of potential inflows and more.

To ensure that the plugging and abandonment operation is pursued properly, NORSOK D-010 (2021) recommends that the following information should serve as a concrete base for well barrier design and abandonment program:

1. Well configuration (original, intermediate, and present) including depths and specifications of permeable formations that are source of inflow, casing strings, cement status behind casing, wellbores, sidetracks etc.
2. Stratigraphic sequence of each wellbore showing reservoirs and information about their current and future production potential including reservoir fluids and pressures (initial, current and in an eternal perspective).
3. Logs, data, and information from primary cementing operations.
4. Estimated formation fracture gradient.
5. Specific well conditions such as scale build up, casing wear, collapsed casing, fill, H_2S, CO_2, hydrates, or similar issues.

4.1 WELL ABANDONMENT PHASES

Normally, in a P&A operation three phases can be defined:

- Phase 1: Reservoir abandonment
- Phase 2: Intermediate abandonment
- Phase 3: Wellhead and conductor removal

These phases are defined regardless of the well location (whether offshore or onshore), well type (whether exploratory, producing, injecting…) and the well status (whether temporary abandoned, suspended, shut-in…). These phases are discussed in detail in *Appendix 4.*

4.2 GENERAL STEPS OF THE OPERATIONAL PROCEDURE

As previously mentioned, each well has its unique conditions therefore having a standard procedure is quite challenging. However, the steps that will be discussed below are considered to be general and common between almost all of the P&A operations.

4.2.1 Data Gathering & Determining Well Conditions:

As a rule of thumb, the more information gathered from a well, the easier will be the planning of any P&A operation. Collecting data regarding bottom hole pressures, well integrity, quality of cement and more, is called well diagnostics which in turn enhances the planning of the P&A operation(s), brings in valuable information in advance, diminishes the risks and reduces the encounter with troublesome situations that could pop up during the operation. Hence, before starting the P&A operation a concrete set of data must be collected.

Data gathering is usually performed by drifting using a wireline or coiled tubing. One of the most important parameters to be determined is the potential inflow from both reservoir and overburden. In addition to that, formations at shallower depths possessing a flow potential must be taken care of. Once the potential inflow in the well has been determined, the plug setting depth calculation can be commenced. As a reminder, the plug's base must be set at a depth where the upward pressure won't exceed the formation fracture gradient. Furthermore, the cement status at these depths needs to be identified prior to the P&A operation. Determining the quality of cement is normally established by well logging which in turn specifies whether the cement is of good quality or if there might be any potential collapses around the casing.

If several wells are scheduled for P&A operation, it is a common practice (adopted by the oil and gas industry) to organize this operation in comprehensive campaigns. This type of planning is typical in large fields like Valhall and Ekofisk which in turn renders the operation to be organized and cost-effective.

4.2.2 Verify/Test Surface Equipment Integrity

Prior to any activity that may take place during the P&A operation the wellbore conditions and surface equipment integrity must be tested and assessed thoroughly. It is extremely important to test the surface equipment due to the fact that they have dual function during well intervention (they operate as both primary and secondary barrier). Thus, every WBE that might be exposed to pressure must be tested for integrity and functionality.

4.2.3 Prepare the Well:

The downhole safety valve (DHSV) can be retrieved only when the wireline (WL) equipment has been installed which in turn are also used to check the wellbore conditions and confirm the tubing's ID (internal diameter).

A DHSV is a safety device installed in the upper part of the well to provide an emergency shutdown when necessary. All wells on the NCS are obliged to install a DHSV at least 50m below the seabed. There are two types of SSSV(s) (subsurface safety valves) used today in the industry, one is surface-controlled, and the other is subsurface-controlled. Both valves are devised to be "fail-safe" which means that in the case of any system failure or damage to the surface control facilities, the wellbore will be immediately isolated.

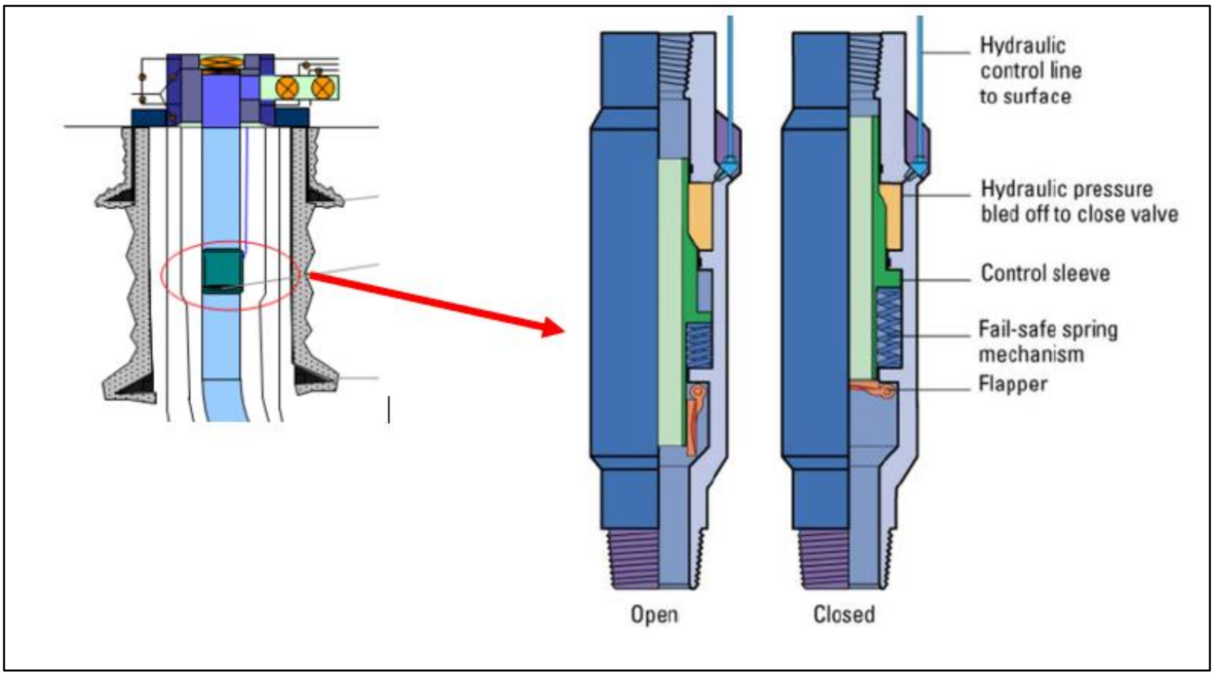


Figure 7: *DHSV: Open vs. Closed position. (Source: TPG4215 NTNU Compendium)*

Normally, the wellbore is examined using a slickline unit which consists of a hydraulically controlled spool of wire utilized to place and retrieve tools and flow-control equipment downhole. Prior to plugging operations, the tubing might require some cleanouts for it might have been subjected to damages during production (e.g., corrosion, collapses, erosion…). It is also very crucial to mend the wear that could happen during interventions and keep the tubing well-maintained since it is a primary barrier element. Furthermore, the tubing must be tested before placing the plug, this is performed by placing a plug downhole isolating the reservoir from the tubing and then exposing the latter to pressure while monitoring whether the pressure holds or not.

4.2.4 Kill the Well:

The first step towards establishing a well that is ready for a plugging operation is to kill the well. Killing a well involves ceasing the flow from the reservoir. This is carried out by placing a column of heavy fluid whose aim is to achieve a hydrostatic overbalance in the well that will prevent the flow of any reservoir fluid and that too without the need of using pressure control equipment at the surface. The principal behind this procedure is that the weight of the kill fluid must be high enough for it to overcome the pressure of the fluids in the reservoir. However, it is very important to keep an eye on the pressure build-up during the killing process for it shouldn't surpass the wellhead pressure rating, casing or tubing burst pressures or even the formation gradient otherwise the kill job would be inadequate (Oudeman et al.,1994).

There are several techniques to execute a well kill operation, but the most used ones are: reverse circulation and bull heading.

- ***Reverse circulation:*** is the process of pumping the kill fluid down the annulus and up through the tubing just above the production packer. This process involves a communication point (normally a perforated interval) through which the kill fluid can migrate. Eventually, the lighter wellbore fluids will be displaced by the kill fluid favoring the increase of the hydrostatic pressure.
- ***Bull heading:*** is the process of forcing fluids back into the formation (Oudeman et al., 1994). Normally, in a bull heading operation, the kill fluid is pumped down the well to compress the fluid in the tubing and force the wellbore fluids back into the reservoir formation. The pumping of kill fluid persists until it completely replaces the reservoir fluids in the tubing and wellbore. This implies that, the volume needed to kill the well can be limited which in turn makes bull heading an effective and rapid process.

The well is killed once the WH pressure disappears. Thus, it is time to enter the wellbore and start setting the plugs.

4.2.5 Retrieve/Pull the Tubing:

Pulling the production tubing out of the hole is not a must and some guidelines allow the operators to leave them in the hole as long as permanent barriers are set through and around them. In most of the cases, removing the production tubing is necessary and that this because of the control lines being attached to it more frequently, hence creating a potential path for fluid escape. According to NORSOK D-010 (2021), control lines and downhole equipment can induce loss of integrity by creating potential leak paths and that this the main reason behind why they cannot be considered part of a permanent well barrier.

Another reason why it might sometimes be necessary to cut and retrieve the tubing out of the hole is because of the existing technologies which are incapable of verifying the cement quality through multiple casings (Moeinikia et al.,2014). Therefore, the tubing must be pulled out in order to conduct a logging run behind the production casing and evaluate the quality of its cement.

Pulling the tubing can be a challenging operation and it is considered to be a heavy one as well where it necessitates the use of drilling facilities or some other units that can withstand high loads. In some cases, it might be difficult to retrieve the tubing, the only solution will then be is to cut the tubing above the production packer, leave it in the well then establish barriers inside and outside of the tubing.

4.2.6 Wellbore Cleanout:

After the retrieval of the tubing, sludge, scale, fill, swarf (small metal chips) and other debris might be left in the wellbore. Prior to plug setting, the wellbore must be cleaned with cleaning fluids pumped down the tubing then up to the annulus. These cleaning fluids must possess a sufficient density capable of controlling the subsurface pressure and physical characteristics capable of removing any unwanted material (Fields et al., 1997). Cleaning the wellbore before plug placement is considered to be a critical activity where one must make sure that the cement plugs shall settle properly, and that no material or sludge shall create an air pocket or move after the cement mixture has been set. It is important to highlight the fact that nowadays a high-pressure jetting system has demonstrated to be an effective and environmentally friendly technique to clean the wellbore.

4.2.7 Log, Cut & Pull Casing and Set Plugs:

At this stage, cement bond logging tools are run into the well to determine the quality of the annular cement. If the log conveys a good quality cement, then a cement plug can be set inside the casing. On the other hand, if the log results indicate poor bonding between the cement and the casing, or no bonding at all then the casing needs to be cut and pulled before setting the plug. In addition to that, and as previously mentioned in section 4.2.5, it might be obligatory to cut the casing for the sake of gaining access to log the cement behind the casing because today's technology is still not powerful enough to effectively log through multiple casings. Cutting the casing is usually performed by the means of section milling or other new techniques which will be projected later on in this project.

So, the first plugs to be placed will be the primary and secondary plugs whose function is to properly seal and isolate the reservoir. In addition to these two plugs, a surface plug which is at much shallower depth must also be placed within this stage. It's important to emphasize that when placing the surface plug, it is sometimes required to cut and pull both the $13\frac{3}{8}$ & $9\frac{5}{8}$ casings for the sake of establishing a plug that extends along the entire well's cross-section (Moeinikia et al., 2014).

4.2.8 Removal of the Upper Part of Surface Casing and Wellhead:

According to NORSOK D-010: "For permanently abandoned wells, the wellhead and casings shall be removed below the seabed at a depth which ensures no stickup in the future." Normally, three or more trips were required to remove each intermediate casing and after that the conductor string was cut and the WH was retrieved (Figure 8). However, nowadays several technologies were developed targeting the reduction of rig time and making it possible to recover either the casing string or the WH in one trip. In addition to that, many technologies aimed at removing the WH without damaging it (when developing the cut & pull technology) in order to reuse it in other projects and thus cutting down the expenses of setting brand new WH equipment. These technologies will be further discussed in chapter 5.

Figure 8: *"Troll A" Wellhead Recovery (as cited in Saasen et al., 2013)*

Finally, the last step is the removal of the platform from site. This stage is usually known as "decommissioning" at which the drilling engineer's job is considered to be done. The decommissioning process can be sometimes a complex operation and hence demands a lot of logistics.

CHAPTER 5: P&A ENGINEERING CONCEPTS, TECHNIQUES & TOOLS

Previously in chapter 4, the operational procedure of the P&A process was introduced in brief. However, in each step of this procedure lies various engineering concepts/ techniques and newly developed technologies that must be highlighted and discussed for they will serve as a ground base in the subsequent digital planning and will be encountered in the excel file prepared in accordance with this thesis. Hence, this section will solely discuss some of these technologies into details especially the ones applied frequently in any P&A operation.

Perhaps the most important step in a P&A operation is the placement of an internal barrier at a required depth in the well, and for it to provide the required isolation a verified external barrier must exist. What is basically meant with an external barrier is the cement of the casing which in turn aims to effectively seal the annulus. Therefore, cement bond logs must be conducted to verify whether the cement possess good sealing capacity or not. Now if the annular seal turned out to be weak, a remedial process must be established within the P&A procedure for example: placing cement in the annulus by different means (section milling, perforating, or circulating etc.), cutting and pulling the casing. Therefore, it is vital to understand what each technique is and what engineering concept behind each is in order to select the most reliable and efficient one for its respective P&A process.

5.1 CUT AND PULL:

The general concept behind the "cut & pull" operation is to target areas in the annulus where no cement is present. Normally, these areas cannot be found around the conductor and surface casings due to the fact that they are cemented all the way up to the surface, however around the intermediate and production casings there might be some free points (where a lack of cement in the annulus exists) since the length of cement differs between different formation zones. So how the "cut and pull" technique is conducted is simply as follows:

1. Find a free point by the means of cement logs or stretch tests [2].
2. Casing string is cut above the free point.
3. Casing string is then pulled out of the hole. Note that, if pulling the string from the first attempt was unachievable, a new cut must be performed, and the pulling process must be repeated.

The cut and pull method can somehow increase the rig time since multiple trips might be needed to cut and pull each casing string. Therefore, this method might not be the most efficient, yet it might be the only applicable solution in a certain P&A well scenario.

5.2 SECTION MILLING:

As previously mentioned, some wells that are scheduled for P&A might contain poorly cemented areas and therefore the only way to gain access to these areas is by removing the casing and the cement behind it. Normally, whenever the casing strings cannot be cut and pulled, the section milling technique will thus be implemented.

Section milling requires grinding and cutting away a section of the casing steel and constructing access windows to fresh formation where a proper permanent barrier/plug can be set. Then, a clean-up operation must be carried on which in turn aims to clean the open hole from the produced swarf [3] and other debris. Afterwards, an under-reaming operation is conducted to make the open-hole larger and thus expose new formation. Finally, and after making sure that all the previous steps were successfully established, the placement of a balanced cement plug in the open hole section shall be fulfilled.

NORSOK D-010 developed a decision tree that can be applied when section milling is required to establish well barriers. This decision tree, found in *Appendix 5*, serves as a starting point to our P&A digital planning which will be discussed later on within this thesis.

Section milling is considered as an unpopular operation during P&A. In other words, it is highly recommended to resort to this technique only when it is the last option left. Section milling is highly problematic; many challenges and risks are expected to be faced when executing this technique some of which are:

- It is a time-consuming operation which indicates that it would increase the time on rig and thus increase the costs incurred. In addition, the milling operation entails the use of a drilling rig which itself is expensive.

[2] Stretch test is performed using a wireline tool with a free-point indicator that operates by detecting stretch in tubular when tension is applied to the surface. Normally used to find the free point of a stuck drill pipe.
[3] Metal fillings or shavings created by the milling tool during the casing removal process.

- Generally, milling operations generate considerable amounts of swarf left behind in the wellbore. In order to suspend and transport swarf to surface while keeping the opened hole stable, the fluids designed for section milling must have adequate weight and viscosity. However, sometimes the required viscous profile of the designed fluids boosts the equivalent circulating density (ECD) to exceed the fracture gradient, resulting in fracturing the formation. This phenomenon may in turn lead to fluid loss and subsequently swabbing and loss of well control. Presence of fluid loss also causes poor hole cleaning and risk of packing off the Bottom Hole Assembly (BHA) which can favor the sticking of the milling or under-reaming BHAs (Khalifeh & Saasen, 2020).
- Swarf imposes high damaging risks on equipment such as the BOP where it can accumulate in critical areas/cavities such as the ram and annular seals.
- The handling and disposal of the produced swarf and debris possess risks linked to health, safety, and environment (HSE). The returning metal shavings usually have sharp angled surfaces, hence personal protection must be accounted for especially eye and skin protection. Therefore, swarf requires a special handling system.
- Milling knives can wear out so quickly (only after some feet of milling), therefore frequent trips for replacement are required.

In order to conquer some of the challenges listed above, the industry worked hard on redeveloping the cutting tools used in section milling (Figure 9). In addition, some new techniques have been introduced as an alternative to the conventional milling such as: PWC (Perforate, Wash and Cement), upward milling, plasma-based milling and more. However, this thesis will just discuss the PWC technique as an alternative, due to the fact that it is more popular/ applicable than the other two techniques mentioned.

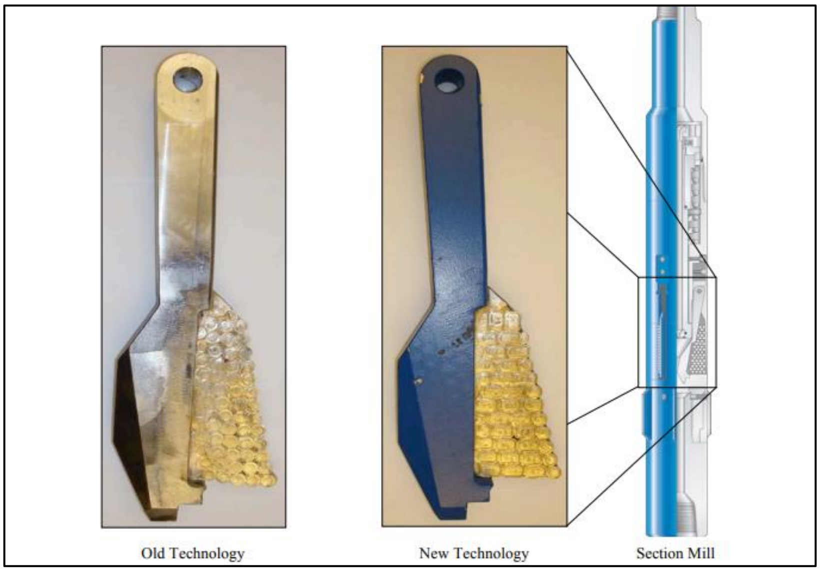


Figure 9: *Previous Cutter Design vs. New Cutter Design, and Section Milling Tool (Stowe & Ponder,2011)*

5.3 PERFORATE, WASH AND CEMENT:

Due to the fact that conventional section milling possess various challenges, finding an alternative was a must. The Perforate, Wash and Cement system (PWC) has been introduced to eliminate some of the challenges that were addressed above.

The main concept behind this technique is to create a permanent well barrier by the means of a system that perforates a section of uncemented casing, washes the annular space and then mechanically places the cement across the wellbore cross section in a single trip. Figures 10 and 11 fully summarize how this technique is conducted. This thesis will not dive any further into the details of this operation since it is out of the scope and the purpose is solely to highlight it and make the reader familiar with this engineering concept.

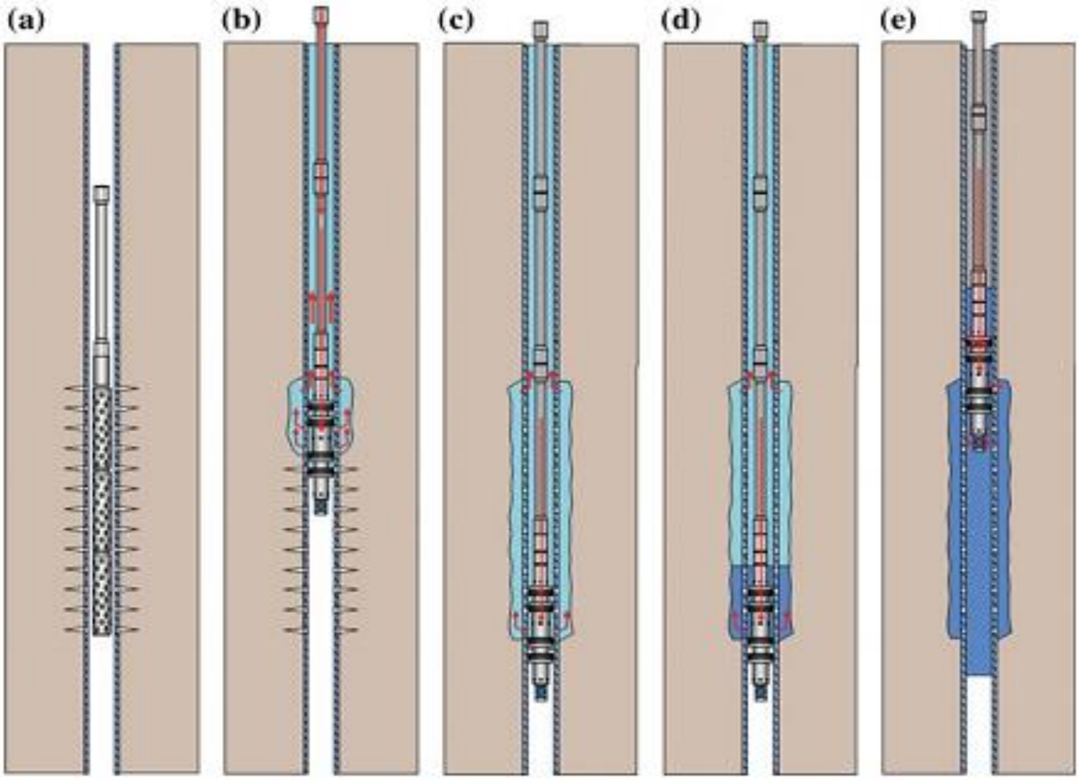


Figure 10*: Perforate and wash part of PWC technique;* ***a*** *casing is perforated,* ***b*** *washing tool is RIH and washes the annular space behind the perforated interval, downward,* ***c*** *BHA is placed below the bottom perforations,* ***d*** *spacer is pumped, and work string is pulled upward,* ***e*** *spacer is extended above the top perforations. (As cited in Khalifeh & Saasen, 2020)*

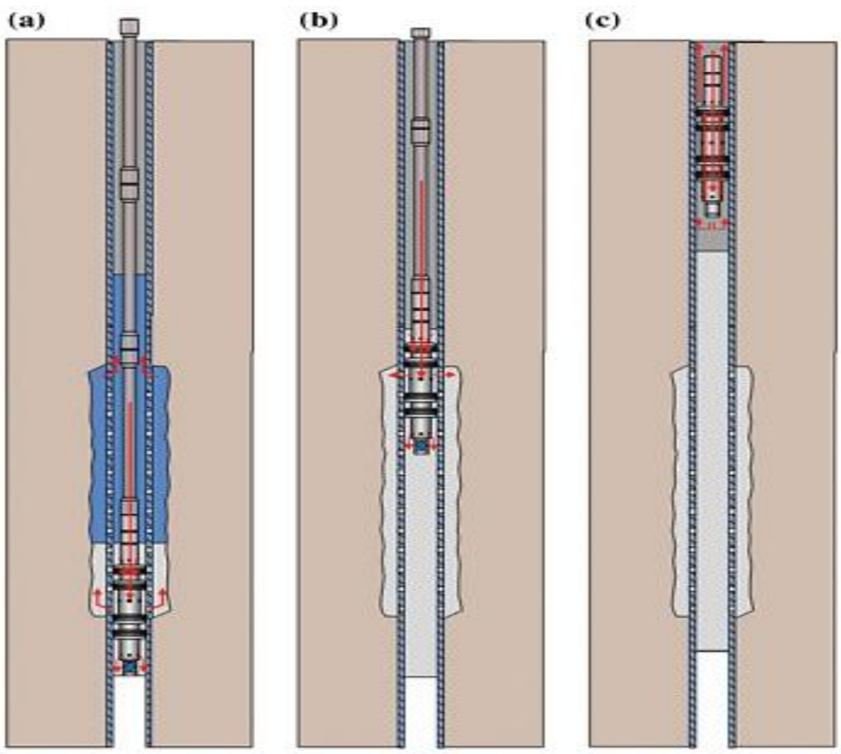


Figure 11: *Cementing part of PWC technique;* ***a*** *BHA is placed below the bottom perforations, pumping few volumes of cement,* ***b*** *pump-and-pull while cementing,* ***c*** *pump cement and circulate out the cement in BHA, pull the BHA out of cement, at least 2 stands above top of cement. (As cited in Khalifeh & Saasen, 2020)*

5.4 Cement Plug Placement Techniques

Placing a cement plug has perhaps been a difficult task over decades. Usually, it takes several attempts to successfully set a cement plug at the originally intended depth and that too with a sufficient strength. Many studies ensured the fact that the success of any cement plug solely depends on the placement technique being followed.

In an ideal operation, the process of placing a cement plug involves the pumping of cement slurry down an open-ended tubing/ drill pipe with return in the annulus. Normally, for the sake of a uniform placement of the cement and the spacer[4], the pipe/tubing must be centered in the wellbore where the cement would be able to make a complete reversal flow in the annulus of the pipe/tubing. However, real life plug placement scenarios are not ideal or simple as they might look like and that is because of several downhole conditions capable of altering the entire technique; favoring its failure. Therefore, when it comes to placing a cement plug, several techniques exist which will be discussed underneath.

5.4.1 Balanced Plug

The balanced plug placement technique is commonly applied in any P&A operation mainly due to its simplicity. A work string (tubing/drill string) is run into the hole until reaching the desired depth for the plug base. Once reached, the work string would be surrounded with mud; therefore, and in order to avoid contamination of the cement with mud, spacer and chemical wash are pumped before and after the cement slurry to ensure proper washing of the hole which in turn also ensures the proper wetting of the casing or formation, and to segregate the drilling fluid from the cement. Cement slurry is pumped down through the tubing/drill string and would make a reversal flow in the annulus between the casing or formation and the work string. When the cement slurry level is the consistent inside and outside the work string, the string will be slowly pulled out while maintaining a balanced fluid level at all times (Figure 12).

[4] Special-purpose liquids that are typically prone to contamination, so a spacer fluid compatible with each is used between the two. The most common spacer is simply chemically treated water. Spacers are used primarily when changing mud types and to separate mud from cement during cementing operations. (Retrieved from Schlumberger Glossary)

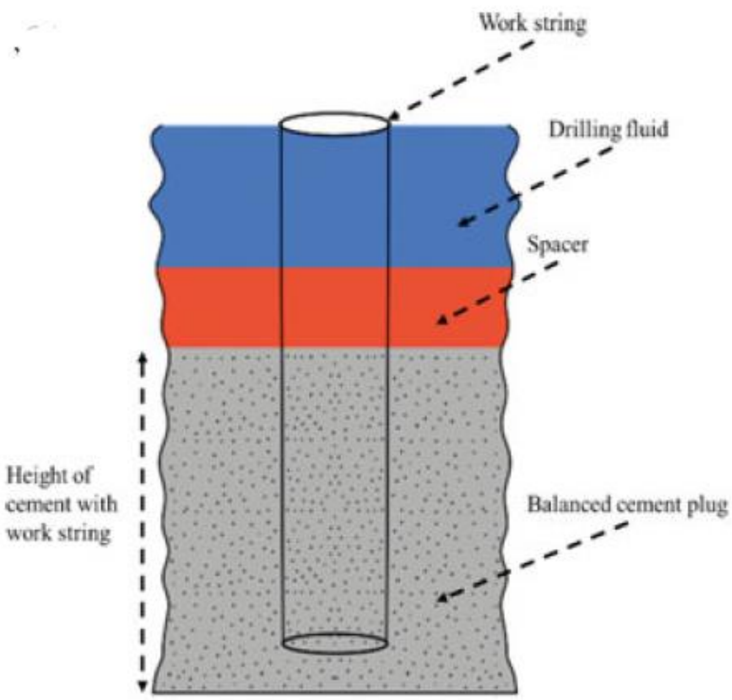


Figure 12: *Balanced-plug placement technique*

One of the main challenges faced when performing this technique is the contamination of the cement slurry. Any contamination of the cement slurry might put its hydration at risk leading to a longer hydration time which in turn could degrade the quality of cement used. According to Diaz et al. (2009), cement plug contamination can occur in four different ways:

1. Mud contamination during pumping
2. Contamination during the flow up in the annulus (between the work string and casing or formation)
3. Contamination caused by cement agitation while pulling the string out of the hole
4. Fluid swapping at the base of the plug due to failed support

A common cause to this problem (cement contamination) has been the downward migration of the cement after placement. According to Harestad et al. (1997), the cement slurry tends to move downwards due to the fact that it is denser than the well fluid, thus the TOC will then be deeper than anticipated. As a result, mechanical plugs or bridge plugs came in handy and helped in avoiding this problem, yet sometimes this support might fail (as mentioned above) leading to what is called: "Fluid Swapping". This thesis will not dive into the technicalities of preventing contamination. However, the best practice to minimize the effect of contamination is to properly design the type, volume and flowrate of spacer and chemical wash or use a two-plug method (Khalifeh & Saasen, 2020).

5.4.2 Two-Plug Method

As previously discussed, one of the placement techniques that can aid in avoiding contamination is the two-plug method. This method ensures that the slurry is fully separated from the spacer thus favoring a drastic decrease of the risk of contamination. Basically, in this technique, a special tool is used in which the cement is pumped with a very high accuracy to a desired depth. This tool, placed at the lower end of the drill pipe, consists of an aluminum tailpipe, a bottom wiper dart/ball which is run ahead of the cement plug (between the lead cement slurry and spacer) and a top wiper dart/ball which is run after the slurry (between the tail cement slurry and spacer) (Nelson & Guillot 2006). Figure 13 conveys a clear explanation on how this method is executed.

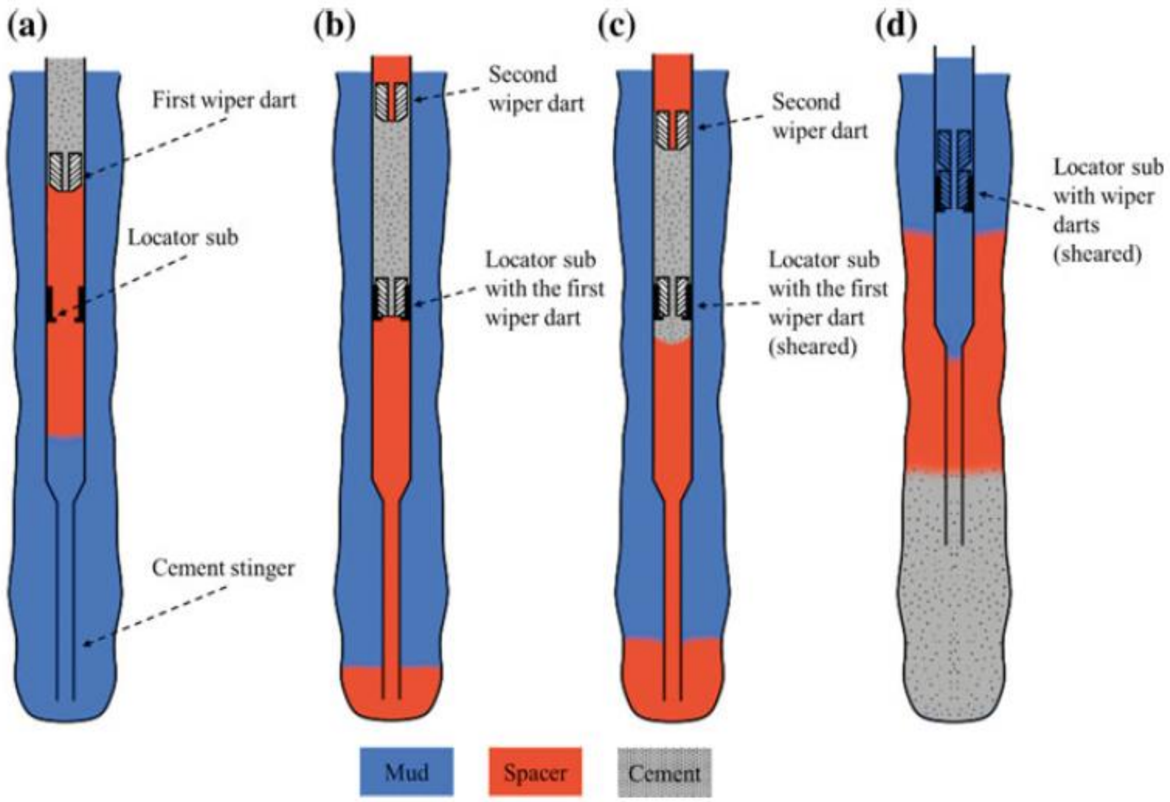


Figure 13: *Two-plug method;* ***a*** *first wiper dart separates cement from spacer until it lands on the locator sub,* ***b*** *second wiper dart separates cement from spacer behind cement,* ***c*** *the diaphragm of the first wiper dart is sheared due to the increased pressure and cement slurry passes through it,* ***d*** *second wiper dart seats on the first wiper dart and its diaphragm is sheared due to the increased pressure and the spacer passes through it. (As cited in Khalifeh & Saasen, 2020)*

This operation should be carefully monitored in order to avoid any formation breakdown or fracturing. Formation breakdown can be easily detected from the volume of the displacing fluid (should be calculated prior to the start of the cementing operation) or from the mud return from the annulus.

5.4.3 Dump Bailer Method

The dump bailer method uses a wireline tool which allows the placement of small volumes of cement at an intended depth with a minimal contamination. This technique is usually implemented on onshore wells or in shallow depths.

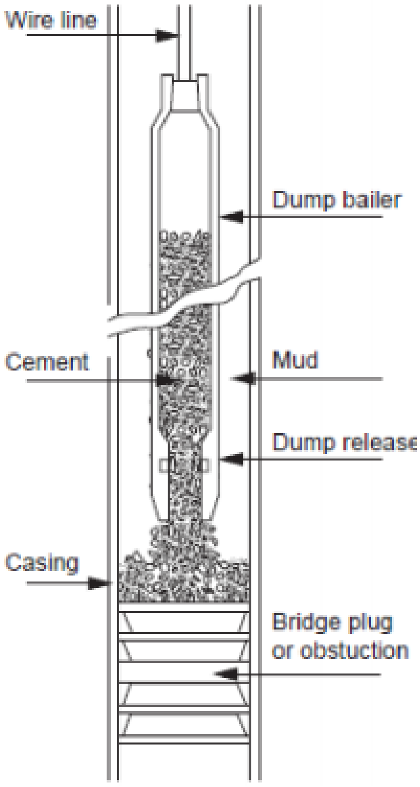


Figure 14: *Dump-Bailer method for plug placement. (Heriot-Watt University, 2010)*

As depicted in Figure 14, the dump bailer in which the cement slurry is contained, is lowered down into the wellbore on a wireline. The moment it reaches the bridge plug, the bailer cap is opened either electronically or mechanically creating a path for the slurry to be released and set on the bridge plug in place. It is important to note that for the slurry to exist the dump bailer, slurry gelation must be taken care off by the means of additives that operate over a wide temperature range. When a dump bailer is decided to be used, it is a common practice to use along with it a mechanical foundation such as a bridge plug (Khalifeh & Saasen, 2020).

The advantages of this method are that the depth control is quite good; it diminishes the risk of slurry contamination and is a relatively rapid and inexpensive means of setting a plug. The disadvantage is that only small volumes can be set due to the narrow capacity of the bailer which in turn means multi runs may be necessary. and it is also not suitable for deep wells unless retarders are employed (Bett, 2017).

5.4.4 Pump and Pull Method:

The Pump and Pull method came out as an alternative method to improve the slurry placement in horizontal and deviated wellbores. When compared to the conventional balanced plug method, this technique allows to spot extended length cement plugs which in turn compensates in reducing rig time and risk associated, however this method entails careful volume calculations with regards to pulling speed and pumping rates, nevertheless it can be a bit challenging to implement in irregular open holes.

Alghamdi et al. (2020), describe the Pump and Pull method as follows: "The method entails spotting a partial (or a well determined volume of slurry) volume of the total slurry in the annulus, this volume which will be around the tailpipe represents a height in the annulus that should not exceed 500ft (preferably) and no less than 200 ft or 6 bbl. whichever is greater, the correspondent volume helps to compensate the lack of synchronization between pumping rates, pulling speed and the washouts in the open hole. The simulation should be run to estimate the free fall and to optimize the spacer's density and volumes. For better placement control, we open the choke and kill line, and we close the backside till the slurry exits the work-string. After spotting the calculated slurry volume in the annulus (the rest of the slurry still in the pipe), the pumping is stopped to prepare for the pump and pull operation, shut down, open the backside, close the choke and the kill line, disconnect the lines, and establish connection to the top drive. Afterwards, resume displacing the slurry with cement unit while pulling the work-string, and the pumping rate shall be synchronized with the pulling speed, in order to avoid contaminating the cement plug, in such way the tail pipe will be kept inside the cement while pulling out." (See Figure 15 for better understanding of the technique).

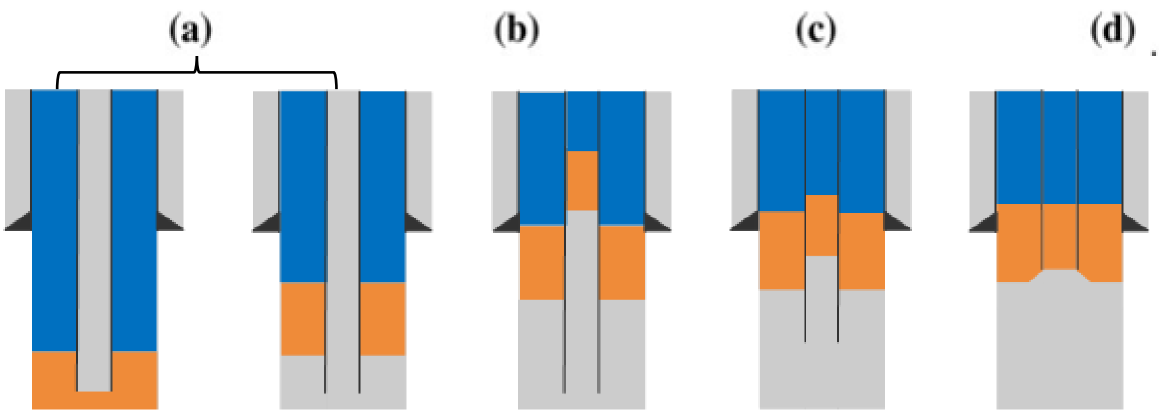


Figure 15: *Pump and Pull Technique;* ***a & b*** *displace the cement slurry according to pre-calculated pumping schedule,* ***c*** *pump and pull out theoretical TOC. Close annular while breaking connections to avoid u-tubing,* ***d*** *dump remaining cement slurry in DP on top of cement plug. (Brechan,2021)*

CHAPTER 6: DIGITALIZATION IN P&A

6.1 THE BEGINNING OF THE END

It is estimated that 2637 development wells need to be plugged on the Norwegian Continental Shelf (NCS) in the very near future (Khalifeh & Saasen, 2020). This is not to mention the number of wells (≈ 3000 wells many with slot recovery) that will be drilled on the NCS in the next decades (Birkeland, 2021) which should be added to the statistical number mentioned above. Consequently, this means that the total plugging cost will be approximately 900 billion Norwegian kroner (NOK) out of which 78% of the cost is indirectly paid by the state (equivalent to 700 billion NOK) due to the current tax regulations in Norway (Myrseth, et al., 2017). A better statistical overview of all wells drilled on the NCS and wells that need to be plugged and abandoned can be seen in Figure 16 below.

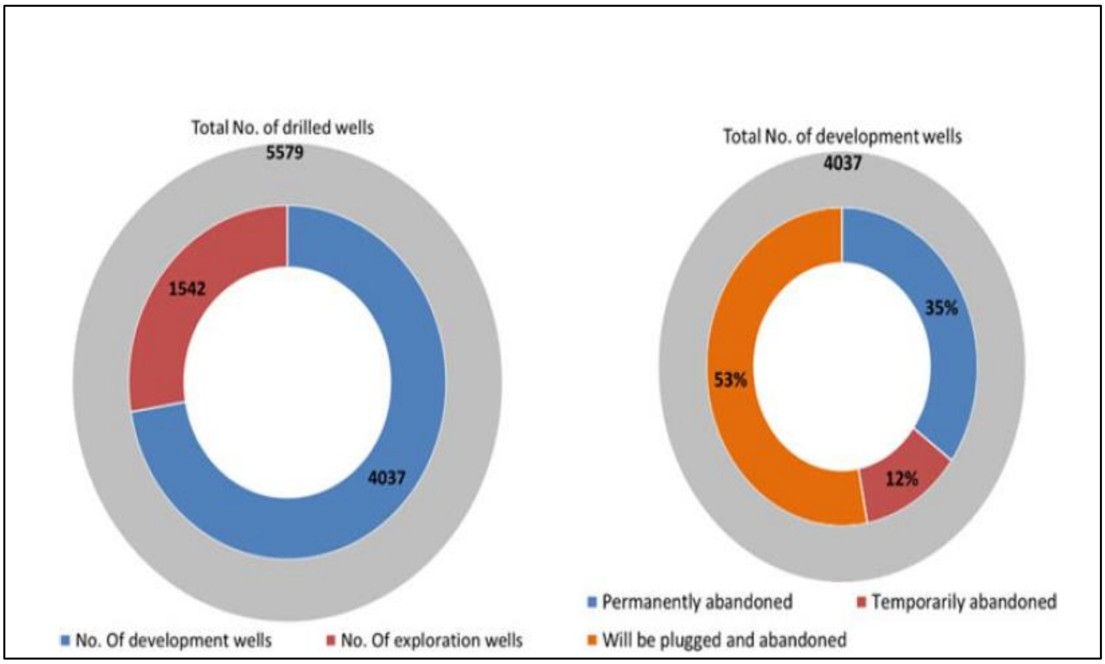


Figure 16: *Statistical overview of all wells drilled on the NCS. (Khalifeh & Saasen, 2020)*

These highly incurred costs of P&A operations urge the oil and gas industry in general and petroleum companies in specific to look into new and advanced technologies that could lead the way towards a cost effective and efficient P&A operation; and here comes the role of digitalization and automation.

6.2 DIGITALIZATION VS. AUTOMATION

It is very important to differentiate between central terms such as digitalization and automation and get to know how they are interconnected. The table below points out the main difference between these two terms.

Table 4: *Automation vs. Digitalization (Retrieved from Brechan,2020) Modified.*

Automation	Digitalization
• Independent of human manipulation • In the context of the conducted research, this means: ▪ *well planning with development of a digital program and administrative tasks (invoicing, logistics, etc.)* ▪ *rigs with equipment fully controlled by software*	• Information and knowledge converted into digital format. • Format usable for software for planning and modelling of integrity. • All info related to wells are available (input to engineering and integrity) linked to relevant engineering and available for planning through the lifecycle of the well. • Integrate with software for operations with automated rig equipment

Digitalization and automation are two interconnected terms. In other words, digitalized information is always needed in order to enable/start the automation process. This thesis will focus on the digital planning of P&A operations where several digitalized information/scenarios will be provided thus establishing a concrete base to start from and move forward towards the automation of the P&A process.

6.3 DIGITIZING OF P&A OPERATIONS

Each year the petroleum industry’s job is becoming more challenging than the year before; where new fields are being discovered in very deep and hard to reach locations, old fields have to be squeezed out till the last drop of recoverable oil is extracted, and costs have to be tussled down. However, nowadays, most of the challenges lie in the P&A operations that need to be run on a huge number of oil wells around the world, out of which an estimate of 3000 oil wells located on the NCS.

Current studies are aiming their focus towards the digitalization of drilling operations. It is important to highlight the fact that digitalization is not a new concept to the oil and gas industry for it has been implemented in the upstream industry for several years (for instance: seismic data processing, monitoring, and optimizing critical production processes…). Moreover, several software has been introduced to the drilling industry such as NOVOS/Drillers Assist (for rig equipment), Landmark EDM (for operational boundaries), ProNova (for operational analysis) and much more.

Currently, for P&A operations, there are no planning software available in the market. The primary plan is to collect all available data linked to P&A operations and combine them into an open-source database which in turn can be developed and used in a P&A planning software. This potential software designed to possess some core benefits such as giving access to huge amount of data, data management, improving accuracy in engineering by employing the latest models and theories, diminishing human error, optimal planning, altering human involvement to a supervisory role and finally contributing to the automation of the process (Brechan et al., 2018).

In 2016, a prototype database has been developed. This database included data on infrastructure, well types and conditions for all wells and wellbores on the NCS. According to Myrseth et al. (2017), the database comprises several tables which can be split into three general groups:

- ***Group 1:*** tables containing information regarding the fields and wells (their location, plugging status, and environmental conditions)
- ***Group 2***: tables containing information about P&A technology performance specifications (such as technology investment and operation costs, time requirements for a certain technology, or probabilities for success if applicable)
- ***Group 3:*** tables linking all the former tables to each other and to the stages of the P&A process for which each are applied.

The figures below convey how the database was supposed to interconnect tables and data entries.

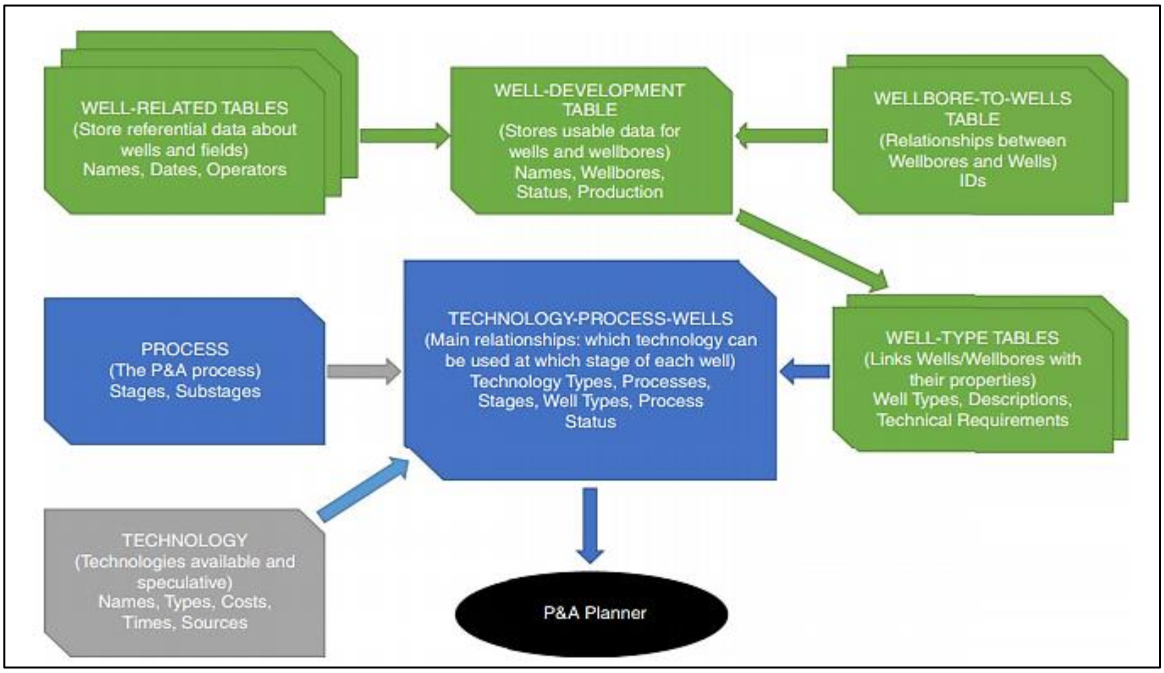


Figure 17: Database structure: Boxes represent tables in the database, and arrows represent the existence of data connections from one table to another, leading to the table(s) input into the P&A planner. (Myrseth,2017)

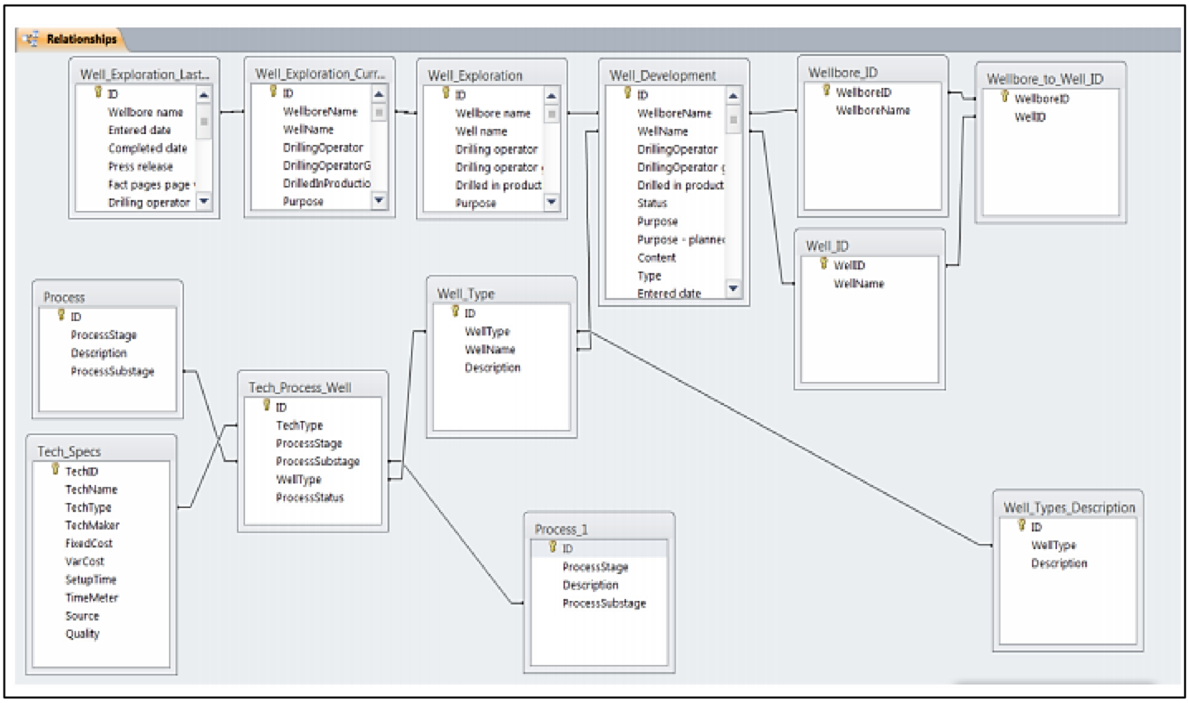


Figure 18: Screenshot of the database window showing how data are currently interlinked. (Myrseth,2016)

In their papers " Norwegian Open-Source P&A Database" & "Development of a Norwegian Open-Source Plug-and-Abandonment Database", Myrseth et al. (2016, 2017) mentioned that the database has been filled with publicly available data provided by the Norwegian Petroleum Directorate (NPD). It was also mentioned that their research team has established contact with some operators who were engaged in P&A operations on the NCS at that time, however they faced a major obstacle that had to deal with confidentiality issues, sharing/publishing of data, and time needed to make data available for research purposes. Therefore, it was concluded that the amount of data needed to proceed further with the research was limited which in turn justifies why the research team did not complete their "open-source database" development up until now.

In 2020, Brechan published his doctoral thesis under the title "Framework for automated well planning and Digital Well Management". The main delivery behind his conducted research was the "birth" of a new framework for improving workflows and automation of planning and construction of wells. Eventually, this framework will serve as a concrete base for a software capable of automating several critical well operations such as: well planning, well intervention and well integrity. It is important to note that, the framework described in Brechan's research is mainly built on acquired experience which emphasizes the importance of an open-source database as a starting point towards a well-built automated software.

The vision of Brechan (2020), is a fully built automated software capable of handling the well starting from its planning until reaching its abandonment. The main application deliberated in his thesis is the "Well Operative System" (WOS) whose function is to move data and parameters when and where applicable. Brechan (2020) called this process "Digital Well Management" and titled the platform "Life Cycle Well Integrity Model" (LCWIM). The platform's name was concluded on the basis that life cycle connects to the aspect of the model running and providing active support from planning to final plugging, and that the entangled engineering calculations are crucial to the well integrity and the field it is located in.

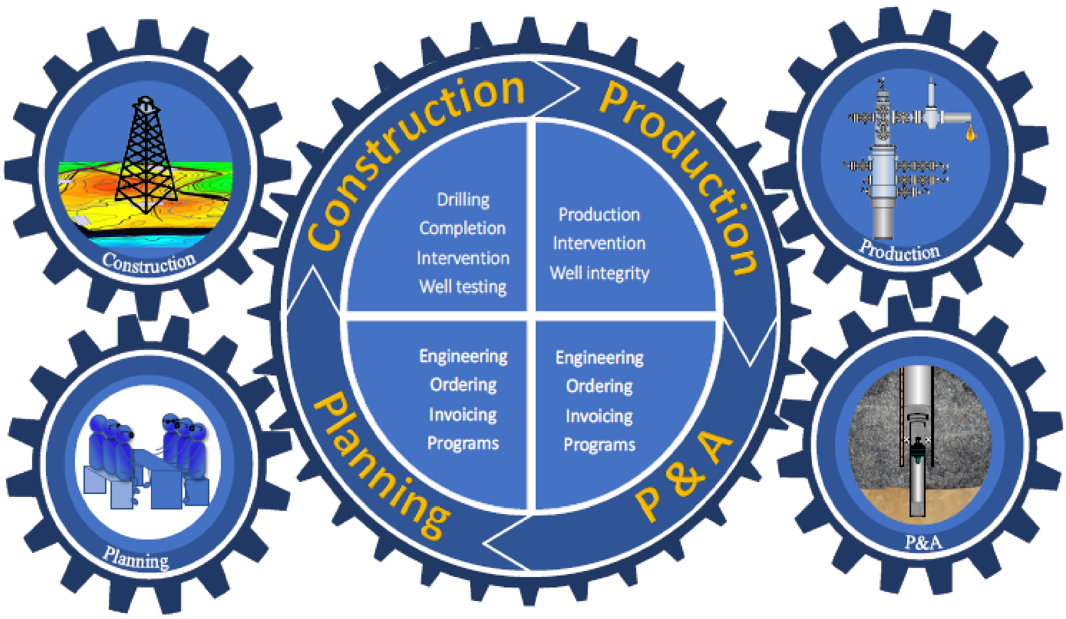


Figure 19: The life cycle of a Digital Well Management (Brechan,2021)

Each of the four phases (Planning, Operation/Construction, Production, and P&A) have a specific team responsible to develop all its aspects accordingly. Nevertheless, many operators make an evident separation between these four disciplines and their goals/outcomes. Brechan (2020) considered this distinct separation a source of disruption for the needs of the wells or projects. He also added that removing some of the walls between these disciplines can bring significant value to the project/well in hand and this can only be achieved when the value chain (portrayed in Figure 19) operates with a fully digital work process.

When it comes to P&A, Brechan (2020) stated that: “There are a few techniques used when plugging wellbores. These can all be described digitally using the reporting language and integrated in the LCWIM. This means that all planning can be automated, based on experience, automatically verified to be compliant with governing documentation and the planned software can provide digital procedures where there is automated rig equipment.” He also gave examples on how the LCWIM can be integrated in P&A operations such as providing detailed cementing calculations and setting a balanced cement plugs fully automated.

CHAPTER 7: SCOPE OF WORK

Starting from the vision Brechan (2020) shared in his published doctoral thesis, this master thesis came into light trying to establish and fine tune a digital program capable of conducting the desired tasks that Brechan (2020) has discussed in his doctoral thesis. The digital program Brechan (2020) mentioned includes several key aspects related to drilling and well engineering. Therefore, and as a starting point, the work was divided between three master thesis candidates where each was responsible about a separate discipline of well engineering. The three disciplines targeted this semester were: Completion, Intervention and P&A.

Although this thesis was done individually, yet the ultimate final goal is to combine all well engineering aspects into a single digital platform, thus eliminating all existing boundaries between these disciplines. However, connecting disciplines together is quite an advanced phase and must be done at the end after all disciplines are fully developed. Now that this is still the first phase of developing a digital software, it was a wiser to divide these disciplines and work on each individually. This part of the thesis will describe how to establish a digital software for P&A operations, what is the best practice and how the program is supposed to work. It is important to note that this program is an underdeveloped prototype which will provide some examples on how P&A operations can be planned. This prototype needs to be further developed and linked to other disciplines due to the fact that P&A operations enclose several engineering concepts e.g., section milling, cement plugging, pumping, intervention and much more which in turn are also connected to other disciplines.

7.1 SOFTWARE'S STATUS AND PLAN:

It is believed that the first step towards being able to digitalize and optimize P&A operations is to collect all obtainable data and integrate it in a format usable by modeling tools. This involves technical data on operational sequences and different techniques that may be resorted too during any P&A operation.

As previously mentioned, the software developed is still at its initial phase where it lacks a lot of algorithms and connecting dots that in turn aid in the process of automation. The concept behind this software is to build decision maps (dependent on the user's input). In other words, the aim behind this software is to guide/lead the user step by step and that too depending on what task/activity he/she are opting for.

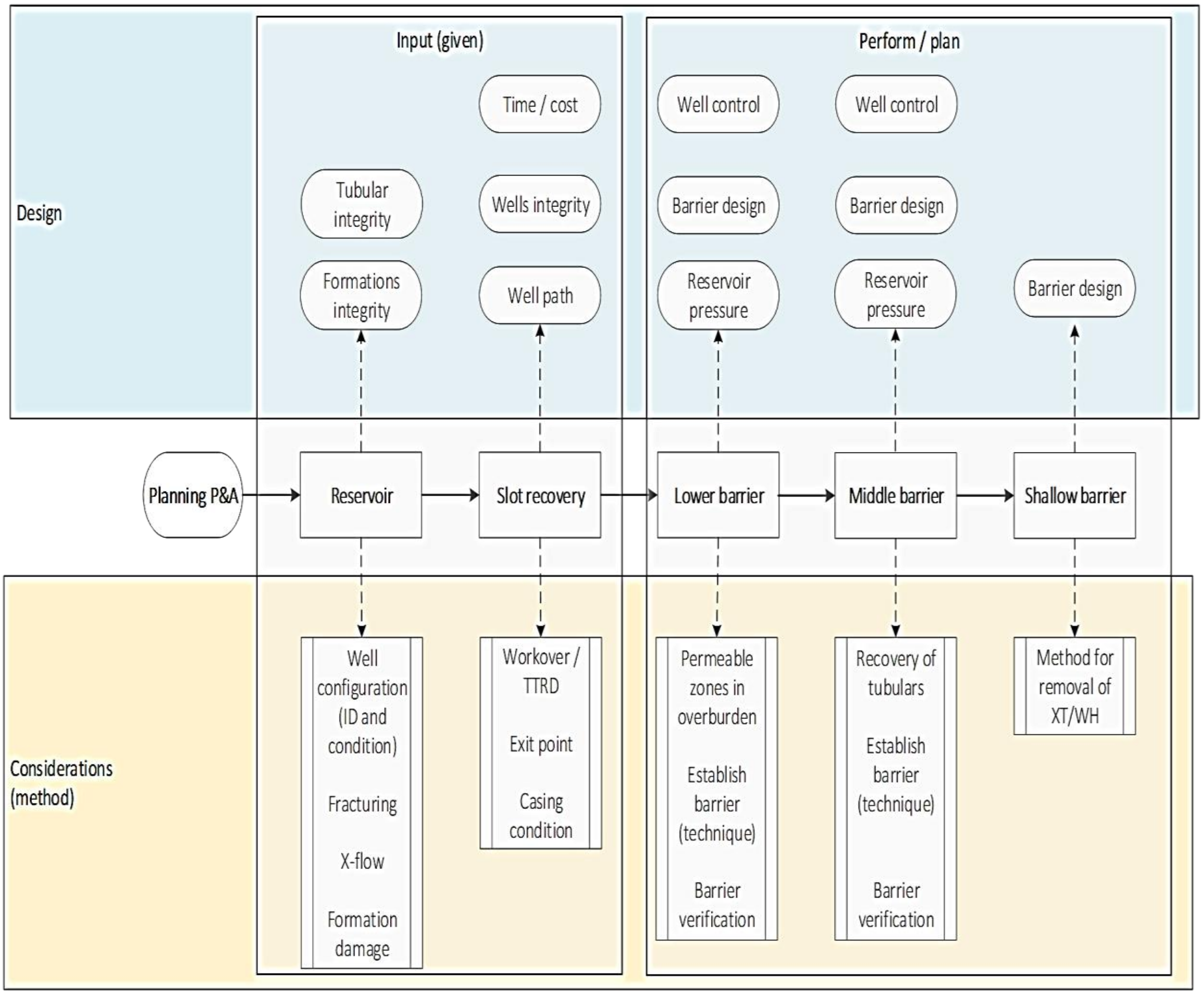


***Figure 20**: P&A preliminary decision map (example) (Brechan,2021)*

Figure 20 shows a preliminary human-based decision map. The plan is to introduce all these tasks into the software being designed along with an algorithm that makes it smart enough to determine what step must be next or what input does it require to move forward to the next step. The figure above presents several disciplines such as well control, well integrity, barrier design, etc. and each one of them must be developed aside and then connected to P&A. This task is quite challenging and fulfilling it requires more time, open-source database along with the professional experience. Due to time and resource limitations, the prototype presented in this thesis will tackle few disciplines providing specific examples in each.

7.2 SOFTWARE FEATURES AND CONFIGURATION

It was first decided to use “Python” programming language to develop the software desired. However, due to time limitations and for the sake of simplicity the prototype was designed using Excel-Microsoft Office.

This section will present different aspects of the software developed and how does it function. Nevertheless, many further developments are necessary to make this software of great value. The future developments will be discussed in section 8.2.

The very first sheet of the excel file is titled: “Well Information” and is conveyed in Figure 21. As a start-up, the user must insert all the information needed (Well name, type, scope, etc.) which in turn will be used for reporting at the time being.

General Information			
Well	Name	Type	Reservoir
Objective/Scope			
Summary of planned events			

Figure 21: Sheet 1 in digital program - Well General Information

The second sheet of the file (see figure 22) mainly represents the main page which is basically the “main application” or the “brain” to the entire software. In this page the user gets to choose the discipline he/she opts to work on which in this case will only be P&A. However, as mentioned before the software will entail several disciplines and the user will get to choose between several well engineering aspects. Then after choosing the discipline, the software will give you an option to choose which section are you interested in developing, where in our case there will be three sections: “Deep Plugging”, “Middle/Secondary Plugging”, and “Shallow Plugging”. In the prototype presented, the “deep plugging” was the only section developed. It is important to highlight the fact that almost all three sections share the same objectives and sequence of events but with minimal changes/conditions. Hence, developing the rest of the two sections won’t consume much of time and effort.

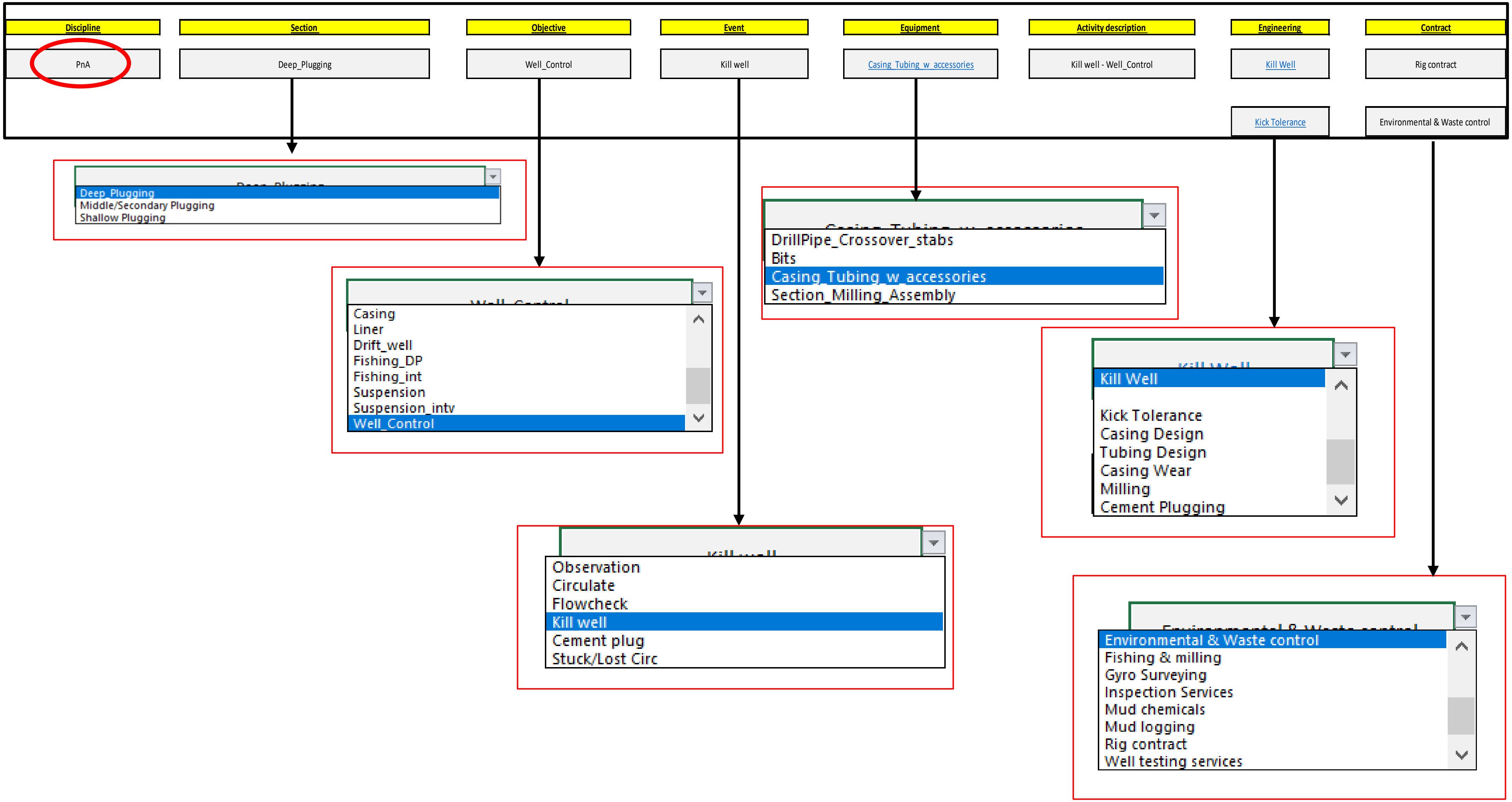


Figure 22: Main Page Layout in digital program

After deciding the section in which the operation will be taking place, the user moves onto choosing his/her objective. As depicted in the figure, the user gets the chance to choose between multiple objectives, and the choice is limited to only one objective at once at the time being. According to what objective was chosen, the event manager will automatically limit the user's choice to a series of events solely corresponding to that objective. For example, in the figure represented above, the objective was "well control" as a result the user gets to choose between: kill well, cement plug, flow check, observation…etc. Nonetheless, if a different objective was chosen, the event manager will display a completely different list of events reflecting the chosen objective. Afterwards, the user must select the equipment needed to fulfill his objective, the list of equipment is hyperlinked to a separate sheet that entails the majority of equipment used. Then the user will have to move further to choose what engineering concept he/she is pursuing and hence deciding what contract[5] shall be needed. The options are limited to two engineering concepts and two contracts due to the fact that some disciplines would require multiple engineering models and contracts. If the user needs only one, he/she can leave the second choice empty or choose "N/A".

7.3 THE ENGINEERING ASPECT OF THE DIGITAL SOFTWARE:

The engineering drop-down list found in the main page of the software is hyperlinked to separate sheets and is fully dependent on the user's selection. This was done to make the software user friendly and make it easy to navigate through it instead of searching between multiple sheets.

In the prototype presented only two engineering concepts were developed to serve as an example of what the software must/can do. These examples will show how useful a digital software can be, and how efficient it can be when it comes to time and effort. This is not to mention the fact that everything connected to P&A will be found in this single file rendering it the state of the art once fully developed.

The two engineering concepts selected were "Section Milling" and "Cement Plugging". These two were preferred since they are strongly associated with each and every P&A operation. The figures and explanation below will convey how do they operate.

[5] Contracts: include people, purchases, and rental equipment

7.3.1 Section Milling:

Milling

Formula Sheet

Input	Abbv.	Value	Unit
Cutting Speed	v	100	SFPM
Cutter Diameter	D	0.625	in
Number of Teeth on Cutter	nt	6	teeth
Feed	f	0.0015	in/tooth
Depth of Cut	d	0.375	in
Cutter Run Out Distance	O	0.3125	in
Length of Cut	L	5.5	in
Width of Cut	w	0.625	in

Select Output

Output: Peripheral Milling	Abbv.	Value	Unit
Rotational Speed	N	611.1550	RPM
Feed Rate	fr	5.5004	Dist/min
Approach Distance	A	0.3062	in
Machine Time	Tm	1.0556	Min
Material Removal Rate	MRR	1.2892	in.cu./Min

Select Output

Output: Peripheral Milling

Output: Peripheral Milling
Output: Face Milling

Select Output

Output: Face Milling	Abbv.	Value	Unit
Rotational Speed	N	611.1550	RPM
Feed Rate	fr	5.5004	Dist/min
Approach Distance	A	0.3125	in
Machine Time	Tm	1.1136	Min
Material Removal Rate	MRR	1.2892	in.cu./Min

***Figure 23**: Section Milling Digital Formula Sheet (example)*

What is shown in Figure 23, is a simple set of equations related to "Section Milling" retrieved from a course taught at Montana State University. These equations were used to develop the excel formula sheet presented above. The set of equations used can be retrieved from the reference list.

How this sheet operates is as follows:

1. The user has to insert the required input (cutting speed, depth of cut, number of teeth on cutter…).
2. After filling-in the needed input, the user gets to choose the desired way of calculating which in our case is either "Peripheral Milling" or "Face Milling".
3. Once the selection is done, the software will present the values accordingly (rotational speed, feed rate, material removal rate…). As it is clearly depicted in the example above, from the very same input we are able to extract distinct outputs using different calculation methods (**Notice**: *approach distance & machine time*).

Apart from developing a calculator, it was noticed that section milling possessed various decision trees/maps. Therefore, it was thought to be efficient if also these decision trees were digitalized which in turn renders decision making easier and time effective. The prototype developed was based on section 9.6.7 in NORSOK D-010 (2013) which can also be found in *Appendix 5*.

Figure 24 reveals a color code on which this digital decision tree is built. It is believed that this color code can be of a good guidance to the user in order to determine what step shall he/she perform next.

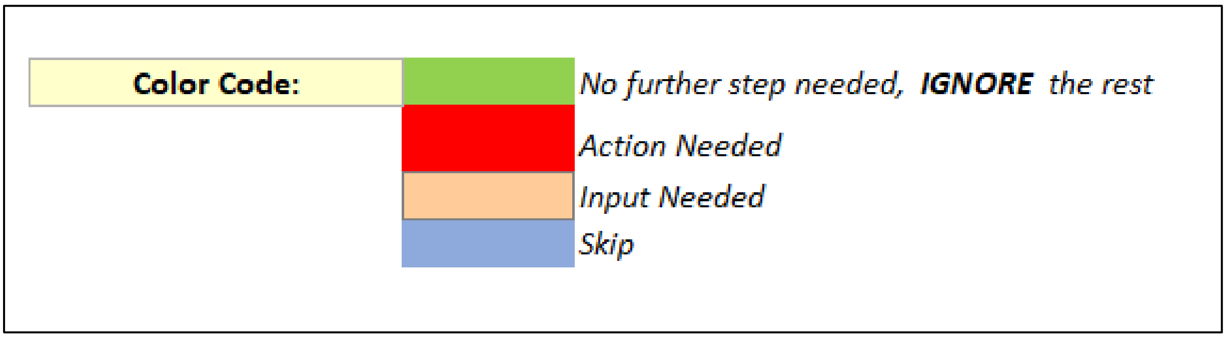


***Figure 24**: Color code for section milling decision tree*

Figure 25 conveys the decision tree developed. Three screenshots of the tree will be presented showing three different scenarios (input/output). It is important to note that this tree is input dependent, meaning that if the input was altered the output will be changing accordingly.

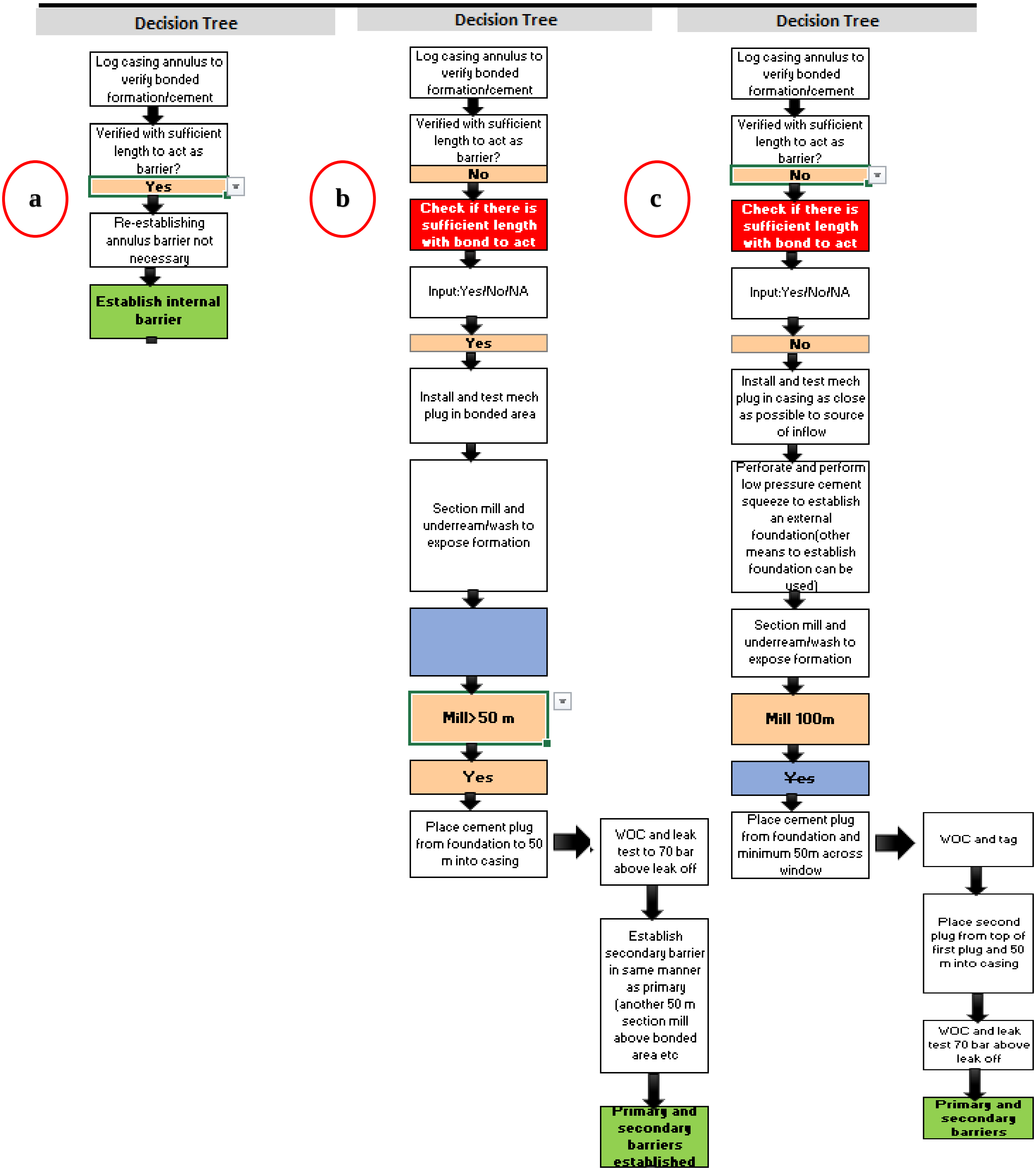


Figure 25: Section milling digital decision tree

The decision tree conveyed above can definitely be more enhanced by the aid of macros or by reproducing it using any programing language.

As a wrap-up, it was clearly seen, from the two basic examples presented, how efficient digitalization can be and to what extent it can be integrated inside the P&A process. In other words, digitalization does not solely result in developing calculators but also can be means of decision making and time saving.

7.3.2 Cement Plugging:

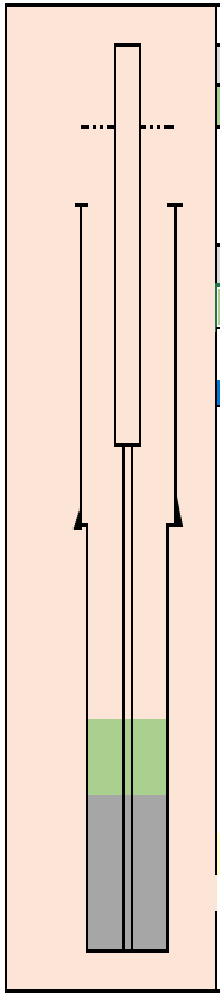
Another example presented in the prototype is the cement plugging calculator. This section is considered to entail a lot of equations (retrieved from "drilling-info" website) and possibilities where much more advancements can be performed and will be discussed in section 8.2.

As conveyed in Figure 26, the user gets to choose between four cement placement techniques (balanced plug, two-plug, pump & pull, and dump bailer) which were already introduced and discussed in section 5.4. In this prototype, the balanced plug method was the only technique developed to serve as an example demonstrating how efficient digitalization can be.

After choosing the cement placement technique (balanced plug method), the user gets to choose the plug setting which in turn are three:

- Plug set in open hole (only)
- Plug set inside casing (only)
- Plug set in open hole and casing

It is important to highlight the fact that the difference between the three projected settings is minimal calculation differences the software is able to alter. After choosing the settings, the user has to fill in the needed input (as shown in Figure 26), then accordingly will obtain the output. Some specifications such as drill pipe or tubing data can be retrieved as well by just pressing on the hyperlink attached which in turn will automatically direct the user to a certified webpage projecting the data needed. After the output is calculated, the program will generate a pumping schedule (Figure 27) demonstrating the results clearly and where they must be employed.



Cement Plugging Technique
Balanced Plug

Plug Settings
Plug set in open hole (only)

Plug set inside casing (only)
Plug set in open hole and casing
Plug set in open hole (only)

Input		
Casing size	7	inch
Casing shoe depth	6000	MD
Casing shoe depth	5500	TVD
Hole size	6.25	inch
Hole Depth	12000	MD
Hole Depth	10000	TVD
Pay Sand Depth Range	9000-9500	ft
Tubing	2 7/8	inch
Tubing ID	2.441	inch
Drill Pipe	4	inch
Drill Pipe ID	3.35	inch

Input: Spacer Design		
Volume	50	bbl
Density	10.5	ppg

*Can be used to extract specifications

Data Tables
Drill Pipe
Tubing

Input: Cement Specifications		
Planned Cement Length	1000	ft
Planned Bottom of cement plug	9600	ft
Top of cement stinger	8400	ft
Height of cement stinger (tubing)	1200	ft
Required cement density	16	ppg
Excess	0	%

Input: Drilling Fluid		
Type	Oil-based mud	
Density	10	ppg

Output: Capacities		
Hole Capacity	0.0379	bbl/ft
Cement stinger capacity	0.0058	bbl/ft
Annular capacity b/w hole & cement stinger	0.0299	bbl/ft
Annular capacity b/w hole & drill pipe	0.0224	bbl/ft
Drill pipe	0.0109	bbl/ft

Output: Cement		
Volume of cement	37.95	bbl
Height of cement while cement string in well	1062.77	ft
TOC (when pipe is in hole)	8537.23	ft

Output: Spacer		
Height of spacer while cement string in well	4.11	bbl
Rest of spacer b/w drill pipe and hole	45.89	bbl
Length of spacer b/w drill pipe & hole	2048.51	ft
Top of spacer	6351.49	ft
Volume of spacer in cement stinger	0.79	bbl
Volume of spacer in drill pipe	22.33	bbl
Total spacer volume in string	23.13	bbl

Mud Displacement		
Volume of mud displacement	69.24	bbl

***Figure 26**: Balanced Plug Cement Calculator*

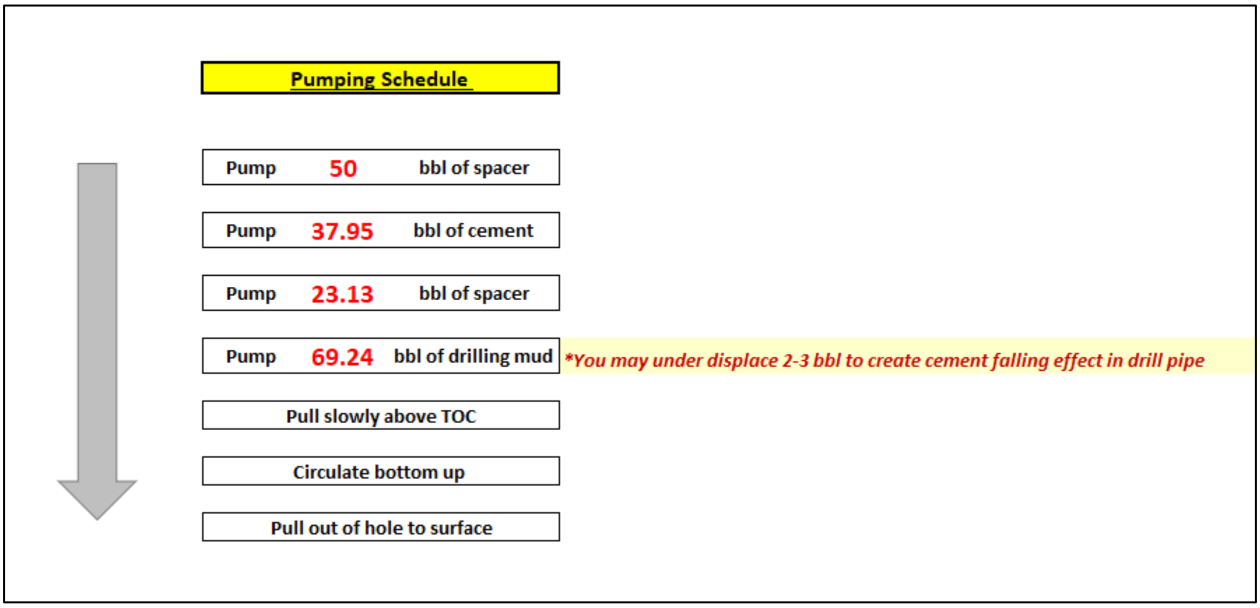


Figure 27: *Automatically generated pumping schedule*

CHAPTER 8: DISCUSSION

8.1 WHAT ARE THE WEAKNESSES OF THIS PROTOTYPE?

To begin with, this prototype is still underdeveloped and lacks a lot of database. There are several objectives/events that need to be fully developed by integrating the necessary calculations and algorithms. In addition to that, the prototype still misses the link between the data inserted. In other words, it lacks the "brains" to connect things together and conclude which variables can be reused. It was also seen that developing this software on Excel possess some limitations, in this case programming would be highly recommended for the digital planning of P&A.

The P&A sector entails a lot of engineering concepts that need to be considered and developed thoroughly such as Pump Design, Casing Design, Torque & Drag and many more. The software so far is not well developed due to time limitation and limited database reach. Therefore, it can be considered a point of weakness which would eventually flip into a point of strength once the digital software is fully built and connected.

Apart from all of this, it is important to shed light on the challenges faced by the P&A sector for they can jeopardize the progress in any digital software being built. One of the major obstacles faced by researchers trying to digitalize P&A operations was confidentiality issues where many operators refused to share data of completed P&A operations. This is not to mention the time and resource limitations that operators possess once they agree on making the data available for research purposes (Myrseth et. al, 2017). Another challenge is that digitalization generates huge volumes of data which in turn are associated with challenges involving data storage & capture, data analysis, data sharing & transfer, data search, data visualization, updating and information security (Murray & Eriksson, 2018). Therefore, developing a digital software will not be enough; it is highly important to address the challenges listed above along the way of digitalization in the oil and gas industry in general and in the P&A sector in specific.

The most challenging part of the digitalization plan will be the digitalization of P&A operations in old wells. It is commonly known that old wells might have some missing/ inaccessible documents detailing the life of the well such as schematic diagrams and well logs. Furthermore, information about the geological history of the well might be lost due to the time (which could be decades) that elapses between well construction and its abandonment. This is not to mention that some wells might have change of ownership. Therefore, the unavailability of information/data could be a real problem in terms of expecting the software to provide all the output needed and that too with very minimal or wrongly assumed input. This problem is now being solved with newly drilled wells which are equipped with sensors capable of monitoring and tracking them starting from their construction and design reaching to their plugging and abandonment. Nevertheless, this does not eliminate the fact that old wells still exist and need to be plugged in the most efficient and least expensive way possible.

In addition to all the challenges mentioned above comes, last but not least, the challenges faced by the P&A sector itself. Some of which are:

- Control lines which create potential leak pathways. According to NORSOK D-010 (2013), control lines shall be removed from areas where permanent well barriers are installed. The only solution so far is to pull the entire tubing.
- Logging challenges where current logging technologies have a short penetration depth making it difficult to log through multiple casing strings. This is not to mention the difficulties that might be faced when reading and interpreting the logs.
- Regulations and guidelines are quite strict. Operators are obliged to adhere to local well-abandonment regulations like NORSOK D-010 in Norway. Normally, compliance requires careful planning and synchronization which, for some operators, may be aided by specialized databases and software. The stringency of regulations can sometimes limit creativity and the “out-of-the-box” thinking, eventually this will contribute to slowing down the work progress. This explains the fact why up till today the petroleum industry is still skeptical of fully integrating automation and digitalization into its sectors. Another challenge faced when it comes to rules and regulations is that they are constantly changing which makes it hard of keeping track of them. According to Barclay et. al (2001), keeping track of continuously changing regulations requires engineering, environmental, legal and safety expertise.

In addition to more challenges linked to casing strings removal, section milling, tubing and casing collapse, and much more.

8.2 Future Work and Developments:

While working on the prototype presented earlier, several ideas were thought off which could make the designed software a “state of the art”. As previously mentioned, the prototype is still on its first “baby” steps and requires more time, efforts and enhancements that aid its metamorphosis into a fully built and well-functioning body. The upcoming list of brainstorming ideas are solely related to the prototype presented which assist in making it rich and smart. These ideas will serve as a good starting point for future work and developments.

1. Develop the software to be smart enough to predict what the user wants from the key words he/she inserted/ typed in. For instance, in the first sheet of the prototype one has to fill the general information of the well out of which there is the scope/objective. The user will have to type in the objective using “key words” introduced to the software before-hand (such as: kill well, pull tubing, log 9 5/8 in. annulus, set cement plug etc.). As a result, the software will start projecting the summary of events that need to be planned (see Figure 28). Once the summary of planned events is complete, the software will automatically adjust the upcoming sheets accordingly; meaning that it will aid in crossing out unnecessary events/objectives from the drop list in the “main page”, highlighting what objectives and engineering concepts must be implemented (where to start from), projecting what is the “best practice”, listing which equipment will be in use, describing what contracts the user has to look in, and automatically obtaining the rules and regulations adhered to the local well-abandonment regulations.

General Information			
Well	Name	Type	Reservoir
Objective/Scope	Kill well Key Word		
Summary of planned events	1. R/U equipment (mud pumps, ROV...) and prepare the kill mud 2. Optional: Run ELSA (Enhanced Landing String Assemble) 3. Equalize and open valves on HXT 4. Pump fluids 5. Flow check well (extended)		

Figure 28: *Automatic generation of planned events in response to "key words" (example)*

2. Regarding the first page of the developed prototype (General well information), many things can be added such as the expected time and cost, risk levels for several risk categories, well conditions and history in the case of dealing with old wells, well barrier status, pressure data, available logs, wellhead info and much more. The more data input, the clearer is the image of the well to the software. It will be as if we are feeding the software information which will help it grow and make the picture clearer to the user. In addition, all the things listed above are used for reporting purposes at the end of the project.

3. It is highly important that this software would have a cloud (database) capable of storing all newly generated reports, cases, and models. This will help the software plan and engineer using experiences automatically which in turn will improve the quality of planning. In other words, the user will build it up to be smarter by adding his/her experience digitally. Experience storage, transfer and reuse can save a lot of planning/ operational time.

4. Moving on the "main page", and more into technicalities, the only section developed was "deep plugging"(as previously mentioned). The software has to differentiate between deep, middle, and shallow plugging by adjusting the differences in objectives and events, in addition to the related engineering calculations.

5. Further development of the equipment list is a must and that can be achieved by linking it to a huge database (only what is contracted). The equipment list should be more precise and entails all the equipment needed for a P&A job. Operators can be contacted to obtain such data.

6. In the prototype presented, the dots are still loose and disconnected, meaning that the excel sheets are still disengaged and missing the algorithm that makes them complete. Some hyperlinks were included in drop-down lists which connect the user to other sheets in the file, yet this is not enough. Connections/links need to be enhanced and more concrete providing the user a smooth transition within the program.

7. Introducing several guidelines to the program such as NORSOK, Oil & Gas UK, Gulf of Mexico BSEE (Bureau of Safety and Environmental Enforcement) and other international guidelines, where the user gets to choose at the very beginning which guidelines he/she wishes to follow. This can be very helpful in terms of making the software a digital product used world-wide. Utilizing the software internationally indicates that more data will be stored in its database, and this in turn will give the software a huge chance to grow bigger and become smarter with all database stored in it. If this step will be applied at any time in the future (even if it is decided to follow only one guideline) it is important to create an algorithm that makes sure that the guidelines are up-to-date and still meet up with the software's working criteria and standards; since as previously mentioned the guidelines are continuously changing and this could lead to a major problem if it was not considered at the very early stages of the software's development.

8. The prototype developed is considered to be an "input-based" digital program. This means that it waits for the user's input in order to generate the output correspondingly. But since this software is supposed to be a planning software, then it would be an efficient idea if the criteria were reversed, turning it also into an "output-based" digital program. In other words, the user will be capable of filling in the output he/she desires and check what input is necessary to obtain such results. This is considered to be a very advanced phase in the software's development, but at the same time it makes it more practical and dynamic. It is important to re-highlight the fact that real-life data is a must in order to obtain realistic results that fit in the P&A process.

9. What also can be added to the software is the option to choose the appropriate vessel to perform the required P&A operation. As it is commonly known there are several vessels each with different specifications. For instance, vessels accessing subsea wells can be classified into three categories:
    - Category A: Riser Less Well Intervention (RLWI)
    - Category B: Heavy Intervention & TTD
    - Category C: Drilling and Completion

Same thing can be applied for drilling rigs which are normally adept at entirely completing a P&A operation, such as: modular drilling rig , specialized P&A rigs[6], pulling and jacking unit (PJU). Integrating both vessel and drilling rig specifications into the software can also be of great advantage for it will fasten the assessment of limitations imposed by them on the P&A process. Thus, the user will have the chance to discover which vessel or drilling rig would be suitable for performing the job. This feature would be highly useful when dealing with the planning of new wells.

10. The software must follow a globally applicable recommended practice such as the one launched by DNV GL at the P&A seminar in Stavanger on the 29th of October 2015. The DNV GL is founded on a risk-based approach where both the risk acceptance criteria are site-specific and the abandonment well design can be well specific. This approach possesses a lot of advantages that can in turn add a great value to the software being developed (DNV GL, 2015) some of which are:
    - Explicit criteria for environmental protection
    - The ability to optimize well abandonment design
    - P&A spending focused on higher-risk wells
    - Site specific considerations
    - Flexibility to make use of new plugging technology in the future

    The main aim behind digitalizing P&A operations was to reduce the incurred costs and integrating a risk-based approach into the digitalization process can ensue more cuts in expenses and result in considerable amounts of savings. *Appendix 6* reflects the necessary elements in well abandonment risk assessment; involving these elements in the software is a must and that too at an early stage.

11. Integration of other engineering tools can be quite beneficial in turning the software into a big factory capable of transforming raw materials into a well-done finished product. Some of these tools could be:
    - A cement calculator that can be integrated within the cement plugging section. This calculator can enable the user to design the cement slurry right at the spot where all additives, retarders and mixing fluid will be listed along with their

[6] A result of collaboration between the Norwegian Rig Company, Gusto MSC and Cameron. It is a custom-built jack-up rig with two dual drilling derricks (as cited in Mortensen, 2016)

specifications. In that way, cement plug calculations will be more realistic and precise.

- Another example could be a leakage calculator like the one developed by Moeinikia et. al (2018). The main objective behind this calculator was to estimate leakage rates through a failed permanent barrier system. It consists of two sets of input: deterministic inputs such as design variables and uncertain inputs, which are presented using probability distributions. As described by Moeinikia et. al (2018), this calculator tackles leakage through bulk cement, through micro annuli and through fractures/cracks.

Such tools and more can exert a great impact on the software developed making it all inclusive.

12. Last but not least, Brechan's (2020) doctoral thesis entails a lot of innovative ideas for establishing a digital program using an iteration sequence. The sequence of the workflow is described in Figure 29 attached below. Applying such a sequence reflects an optimistic future for digitalization in the oil and gas industry.

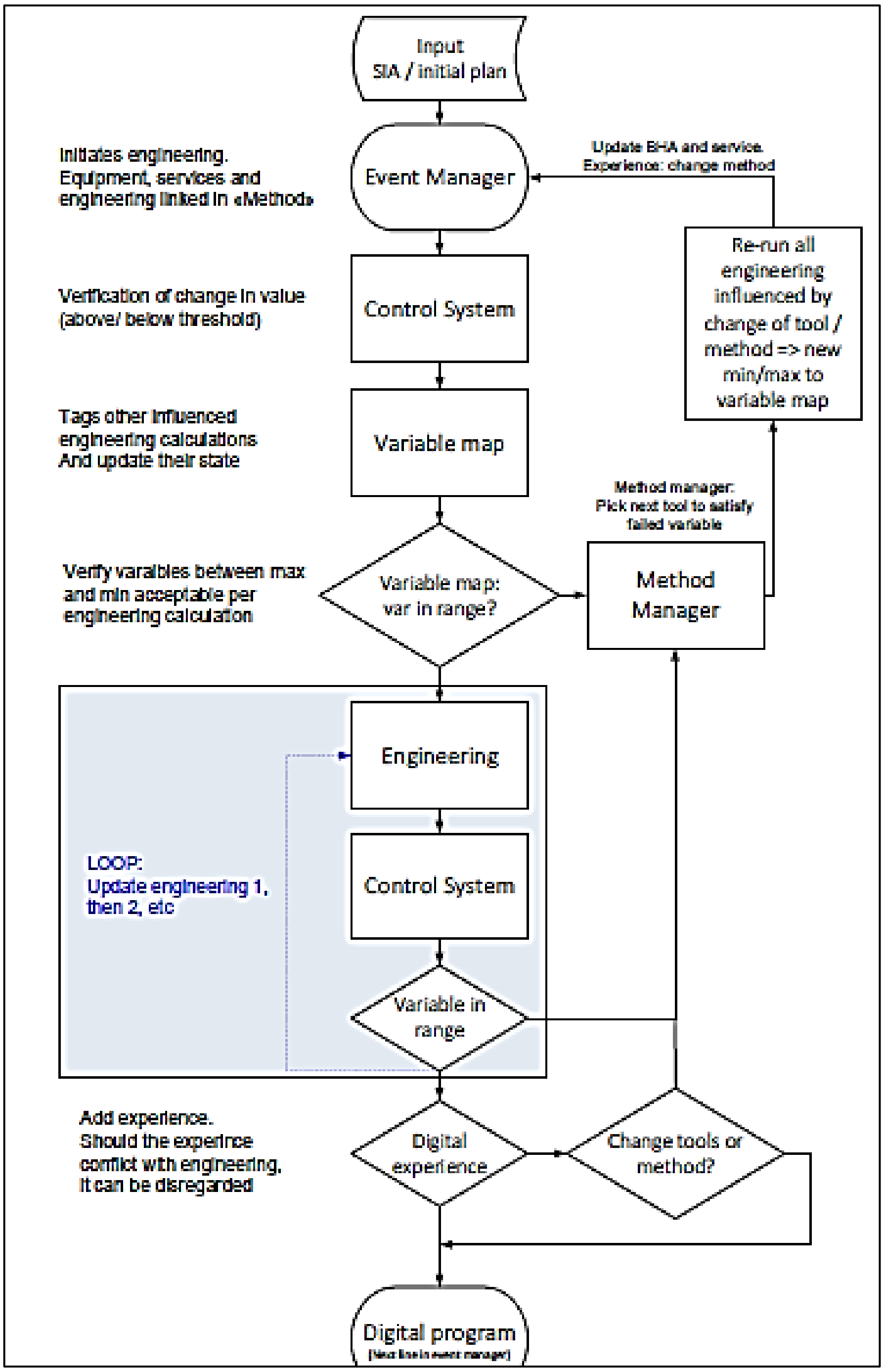


Figure 29: *Overall flow diagram for the "iteration sequence". (Brechan,2020)*

CHAPTER 9: CONCLUSION

The conceptual "life of a well" undoubtedly extends beyond the production phase. Well abandonment is considered to be one of the most essential phases in a well's life cycle, where it involves several complex operations at once such as: well design, cement plugging, pumping, well barrier verification, plugging intervention and much more. Creating a common budget at the beginning of a project for P&A operations can help ensure a less costly and a more efficient plugging of the well. Starting from this point, it is crucial to consider planning P&A operations for future or new wells at an early stage, and that too with legislation enforced since operators will delay P&A planning as long as physically possible. This planning should be done with modern tools and methods such as a dynamic and adaptive digital planning software. Digital processes are capable of enhancing the quality of plans and provide operational support for users.

It is clearly noticed that the petroleum industry, finally, became brave enough to step into the world of digitalization and automation, where nowadays the main focus is targeted towards how drilling activities are conducted remotely with high efficiency, more safety, and less costs. Much software has been integrated into the industry so far, a leading example could be Landmark EDM by Halliburton; this platform is the industry's most comprehensive and proven well data management solution. This software clearly conveys the advantages of digitalization and its effect on the workflow in terms of time and cost.

This thesis presents a ground base to build upon, where a software prototype was developed marking almost all major events, engineering concepts and equipment needed to fulfill any P&A operation. Although, the software is not fully functional, still it serves as unique example outlining how can a P&A process be digitalized. Normally, a digital planning software is capable of enhancing operational performance, storing previous experience, and automatically relating it to other upcoming projects and this is what the author aims to reach in the prototype developed. The future work suggested in section 8.2 is all feasible and can be achieved but requires time, an open-source database, and professional programming skills. Many digital tools/programs related to P&A were developed in the industry, but none were fully comprehensive, all what was established was "bits and pieces".

Digitalization is a huge step, but at the same time it is the key to transformation, and it is the solution to many problems faced by the industry today. Developing a digital planning software that covers all disciplines involved in a well's lifecycle will cause a major transition in the oil and gas industry. A transition devoid of human errors: "the main cause behind repeated failures in operations". Soon enough, the world will be facing a wave of plugging and abandoning wells out of service. This, in turn, should be a motive to integrate digital planning software into the drilling industry and if not in all its discipline, at least in the P&A sector.

On an end note, Johann Wolfgang von Goethe once said: "What is not started will never get finished"; this digital prototype is certainly the starting point towards a fully automated plugging and abandonment operation.

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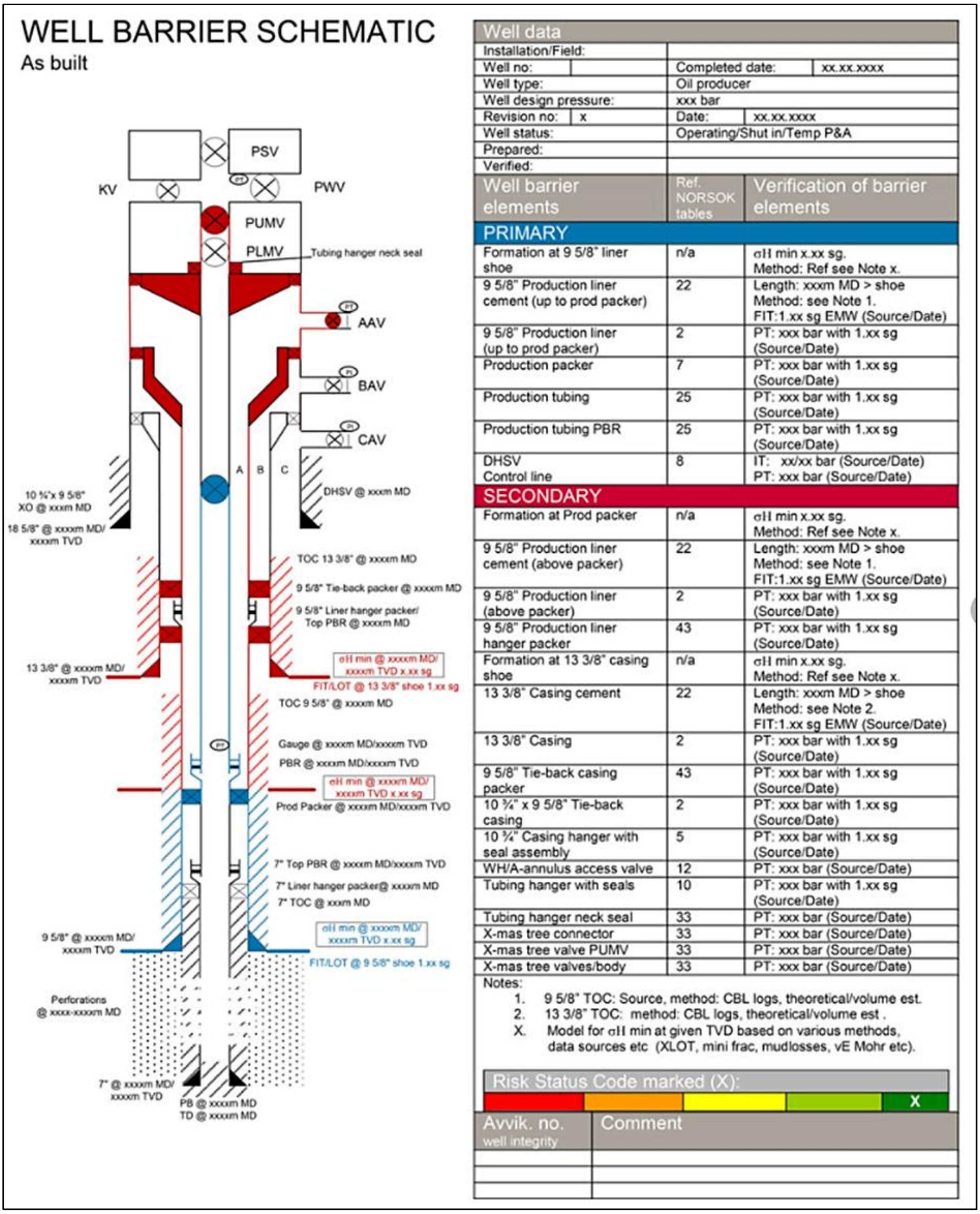
APPENDICES

APPENDIX 1



Well data			
Installation/Field:			
Well no:		Completed date:	xx.xx.xxxx
Well type:		Oil producer	
Well design pressure:		xxx bar	
Revision no:	x	Date:	xx.xx.xxxx
Well status:		Operating/Shut in/Temp P&A	
Prepared:			
Verified:			

Well barrier elements	Ref. NORSOK tables	Verification of barrier elements
PRIMARY		
Formation at 9 5/8" liner shoe	n/a	σH min x.xx sg. Method: Ref see Note x.
9 5/8" Production liner cement (up to prod packer)	22	Length: xxxm MD > shoe Method: see Note 1. FIT:1.xx sg EMW (Source/Date)
9 5/8" Production liner (up to prod packer)	2	PT: xxx bar with 1.xx sg (Source/Date)
Production packer	7	PT: xxx bar with 1.xx sg (Source/Date)
Production tubing	25	PT: xxx bar with 1.xx sg (Source/Date)
Production tubing PBR	25	PT: xxx bar with 1.xx sg (Source/Date)
DHSV Control line	8	IT: xx/xx bar (Source/Date) PT: xxx bar (Source/Date)
SECONDARY		
Formation at Prod packer	n/a	σH min x.xx sg. Method: Ref see Note x.
9 5/8" Production liner cement (above packer)	22	Length: xxxm MD > shoe Method: see Note 1. FIT:1.xx sg EMW (Source/Date)
9 5/8" Production liner (above packer)	2	PT: xxx bar with 1.xx sg (Source/Date)
9 5/8" Production liner hanger packer	43	PT: xxx bar with 1.xx sg (Source/Date)
Formation at 13 3/8" casing shoe	n/a	σH min x.xx sg. Method: Ref see Note x.
13 3/8" Casing cement	22	Length: xxxm MD > shoe Method: see Note 2. FIT:1.xx sg EMW (Source/Date)
13 3/8" Casing	2	PT: xxx bar with 1.xx sg (Source/Date)
9 5/8" Tie-back casing packer	43	PT: xxx bar with 1.xx sg (Source/Date)
10 ¾" x 9 5/8" Tie-back casing	2	PT: xxx bar with 1.xx sg (Source/Date)
10 ¾" Casing hanger with seal assembly	5	PT: xxx bar with 1.xx sg (Source/Date)
WH/A-annulus access valve	12	PT: xxx bar (Source/Date)
Tubing hanger with seals	10	PT: xxx bar with 1.xx sg (Source/Date)
Tubing hanger neck seal	33	PT: xxx bar (Source/Date)
X-mas tree connector	33	PT: xxx bar (Source/Date)
X-mas tree valve PUMV	33	PT: xxx bar (Source/Date)
X-mas tree valves/body	33	PT: xxx bar (Source/Date)

Notes:
1. 9 5/8" TOC: Source, method: CBL logs, theoretical/volume est.
2. 13 3/8" TOC: method: CBL logs, theoretical/volume est .
X. Model for σH min at given TVD based on various methods, data sources etc (XLOT, mini frac, mudlosses, vE Mohr etc).

Risk Status Code marked (X):				
				X

Avvik. no. well integrity	Comment

Figure A 1: Well barrier schematic

One of the most important documents in a P&A operation is a WBS. Understanding what information it holds is a must and can be found in the description below.

- **Well Data:** this section entails all information linked to the well and reflects the status of the well at hand.
- **Well barrier elements:** describes both primary (blue colored) and secondary (red colored) well barrier elements involved in the well barrier envelope.
- **Ref. Table NORSOK D-010:** provides references to NORSOK D-010 general acceptance criteria tables for each WBE.
- **Verification of barrier elements:** describes the requirements for testing which are provided by NORSOK D-010
- **Risk Status Code:** reflects the well's situation and at what level of risk it is

APPENDIX 2

Generally, a formation integrity test is a test pressurized to a pre-defined maximum value during which no leak-off is observed (Addis et. Al, 1998). It is usually conducted on regular basis to measure the formation strength and examine the cement-seal integrity at the casing shoe to a pre-designed pressure. Normally, the FIT is conducted after a section has been drilled, the casing has been run and cemented, then the shoe cement is drilled out completely along with the new hole section to a depth of about 3m in the fresh formation.

The LOT continues the formation integrity test but this time until reaching a point known as the leak-off pressure (LOP) or fracture initiation pressure (FIP). Normally, it is a verification method which aids in verifying whether the casing, cement and formation below the casing shoe can endure the wellbore pressure required to drill for the next casing string safely. The results obtained from this test convey the maximum pressure or the maximum mud weight that can be imposed on that open-hole formation. The leak-off tests are typically demarcated as the point where the pressure plot deviates from a straight line. Once the deviation from linearity takes place, the leak-off pressure (LOP) would then be achieved.

During an ELOT, a standard leak-off test repeated with two or more pumping cycles, the pumping of fluid is continued way beyond the FBP. The pumping continues up until the fracture propagation stabilizes which indicates that the pumping volume is equalizing the increase in the fracture volume (Figure 4). After the pumps were shut, the pressure decline is monitored and a drastic drop in pressure was noticed at which the "Instantaneous Shut-In Pressure" was recorded.

ELOTs are primarily conducted to obtain one of the most important parameters the "Fracture Closure Pressure" which can be obtained using the double tangent method as depicted in Figure 4. This pressure, also known as the minimum formation stress (σ_h), represents the maximum pressure the well can endure without any leakage of hydrocarbons into the formation. As a side note, the second and third shut in pressures provide the best estimates of the formation stress magnitude.

As a wrap up, the depth at which the base of the barriers shall be set must consider all the following parameters: FBP, FCP and the maximum potential internal pressure. The maximum potential internal pressure can be computed using the following equation:

$$\boxed{P_{int} = P_{res} - \rho_f * g * D}$$

Where:

$P_{int} = maximum\ potential\ internal\ pressure$

$P_{res} = reservoir\ pressure$

$\rho_f = lowest\ fluid\ density\ used\ in\ reservoir\ (normally\ gas)$

$g = gravity$

$D = TVD\ at\ the\ barrier's\ base$

APPENDIX 3

Regulation / Case	NORSOK	Oil & Gas UK	BSEE
Open hole cement plugs	At least 100 m MD with minimum 50 m MD above any source of inflow/leakage.	At least 30 m MD, ~153 m recommended. The top of the first barrier should extend at least 30 m MD above highest point of potential inflow.	At least 30 m below and above potential source of inflow to isolate the strata.
Transition from open hole to cased hole	At least 50 m MD above and below casing shoe.	Extending at least 30 m of good cement into cased hole.	At least 30 m above and below casing shoe.
Cased hole cement plugs	At least 100 m MD. If set on a mechanical/cement plug foundation 50 m MD is required.	At least 30 m MD.	30 m. If set on a mechanical plug 15 m is required.
Surface plug	100 m MD. 50 m MD if set on a mechanical plug.	Not directly specified, but at least 30 m MD assumed.	At least 45 m in the smallest casing that extends to surface, with top of the plug no more than 45 m below surface.
Casing annulus cement	50 m MD if verified by displacement calculations, and 30 m MD if verified by bonding logs.	At least 30 m MD if verified by bonding logs, and 305 m MD if verified by parameters from cement job.	At least 60 m in annular space that communicates with open hole and extends to surface.

Figure A 2: *Summary of requirements for barrier length (Jensen, 2014)*

Regulation Case	NORSOK	Oil & Gas UK	BSEE
Plug installation	Evaluation of cement job execution (estimated hole size, volumes pumped and returns)	Records from the cement operation (volumes pumped, returns during cementing etc.).	Not specified.
Strength development of cement slurry	Observation of surface samples from the mixing cured on site in representative temperature (and pressure?).	Pre-job testing with representative downhole temperature and pressure.	Not specified.
Open hole	Tagging.	Tagging. Weight test: • Typically 15,000 lbs. on drill pipe. • If e.g. wireline is used, this weight may be limited.	The first plug below the surface plug and all plugs in lost circulation areas that are in open hole shall be tested. The plug must pass one of the following test: • Weight test of at least 15,000 lbs. on the plug. • Pressure test of at least 1,000 psi. The pressure shall not drop more than 10 per cent in 15 minutes.
Cased hole	Tagging. Pressure test: • 70 bar (1,000 psi) above estimated LOT pressure below casing/potential leak path, or 35 bar (500 psi) for surface casing plug. • Shall not exceed the casing pressure test and the casing burst rating corrected for casing wear. • If set on pressure tested foundation, a pressure test is not required.	Tagging. Inflow test: • At least similar to the maximum differential pressure the barrier will experience after abandonment. Or Pressure test: • 35 bar (500 psi) above the injection pressure below the barrier. • Shall not exceed the casing strength minus wear allowance. • If set on tagged and pressure tested foundation, pressure testing and tagging may not be meaningful.	
Casing annulus cement	Verified by bonding logs or displacement calculations.	Verified by logs (e.g. CBL) or estimated based on parameters from the cementing operation.	Not specified.

***Figure A 3**: Summary of requirements for barrier verification (Jensen,2014)*

APPENDIX 4

Phase 1: Reservoir Abandonment

Generally speaking, this phase is defined as the moment when the primary and secondary barriers are set in place to secure the main reservoir. This means that at the beginning of this phase no barrier has been set against the reservoir, thus full well control must be maintained within this phase.

This phase primarily starts by inspecting the wellhead and rigging up a wireline unit which in turn is utilized to check the access to the wellbore by drifting and evaluating the condition of the production tubing by running a caliper log. The activities within this phase can vary between open hole and cased hole perforated section. For example, in the case of a cased hole one of the most challenging situations could be re-establishing annular barriers as a result of poor cementing jobs carried out behind the casing. This phase could also include the partial or full retrieval of the production tubing or even leaving it in the wellbore as a part of the well barrier envelope.

The reservoir abandonment phase is considered to be complete when the reservoir is fully detached from the wellbore.

Phase 2: Intermediate abandonment

The intermediate abandonment aims to seal zones with flow potential between the reservoir and top of the well and cease communication within the wellbore. The section that this phase tackles is generally known as the intermediate zone and may contain hydrocarbons that could be abnormally pressured or water bearing permeable zones.

Milling, casing retrieval, barrier setting to isolate intermediate hydrocarbon or water-bearing zones, and installation of an environmental plug normally take place within this phase. This phase is considered to be complete when no further permanent barriers are required.

Phase 3: Wellhead and conductor removal

This phase is considered to be the last phase of the P&A operation. Basically, in this phase, the conductor and wellhead are cut few meters below the seabed so that nothing coming from the well would extend above the seabed. This phase can be considered to be a part of the decommissioning phase also. It is important to note that, on the NCS this phase is considered to be a marine job and not a drilling operation. After this phase reaches an end, the well is considered to be fully abandoned where it will never be re-used nor re-accessed again.

APPENDIX 5

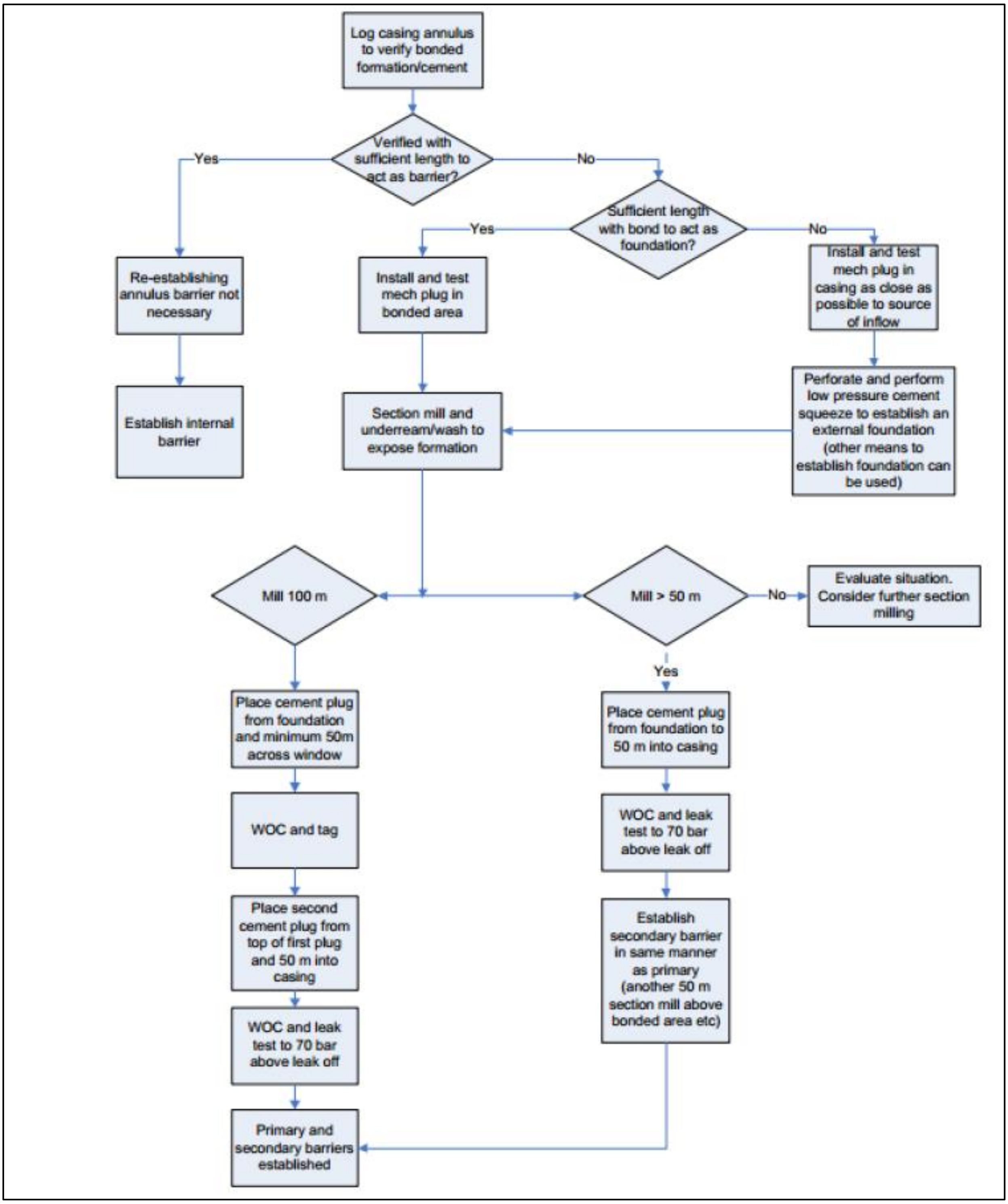


Figure A 4: *Section milling to establish well barriers (NORSOK 2013, p.107)*

APPENDIX 6

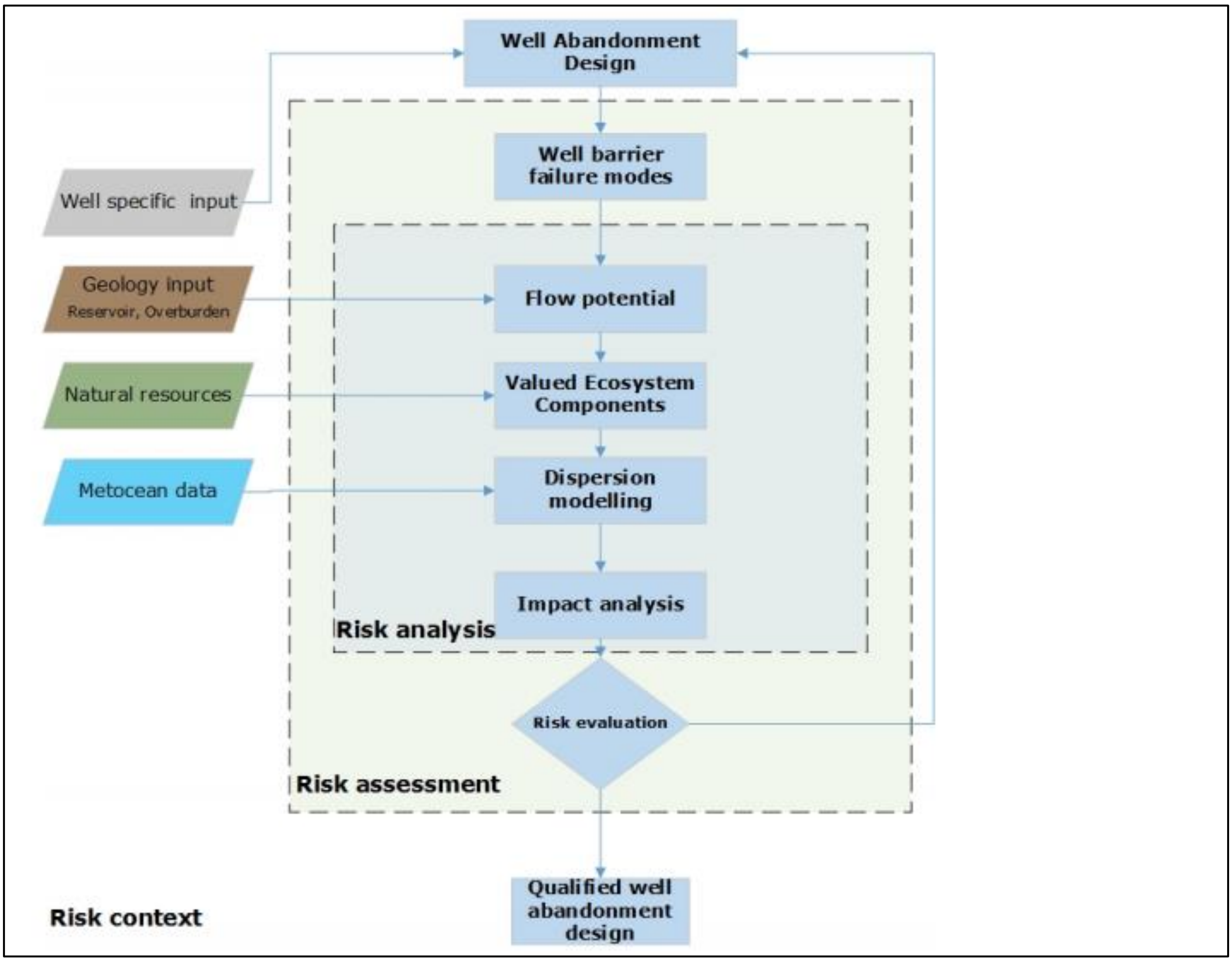


Figure A 5: Elements in well abandonment risk assessment (DNV GL,2015)

APPENDIX 7

Excel file Instruction Manual (*for user*):

1. Fill in the well's general information which will be used for reporting and for other purposes later on.
2. Choose the section on which the planning will be carried (deep, middle, or shallow)
3. Choose the objective for using this software. Once the objective is chosen, the list of events will pop up accordingly.
4. Choose the list of equipment needed to fulfill the objective.
5. Choose the relevant engineering concepts for the objective previously chosen.
6. Finally, decide what contract will be involved in the operation being carried.

The excel file consists of several sheets that can be accessed/ modified separately for further use.

The components of the excel file are projected in the figure below. All sheets starting with "C_" represent a certain contract. These sheets can be all found in sheet 5 in which they are also hyperlinked. Sheet 13 entails some engineering concepts linked to P&A, two concepts were developed which are section milling (sheet 14) and cement plugging (sheet 3). The excel file is not fully functional and requires various enhancements.

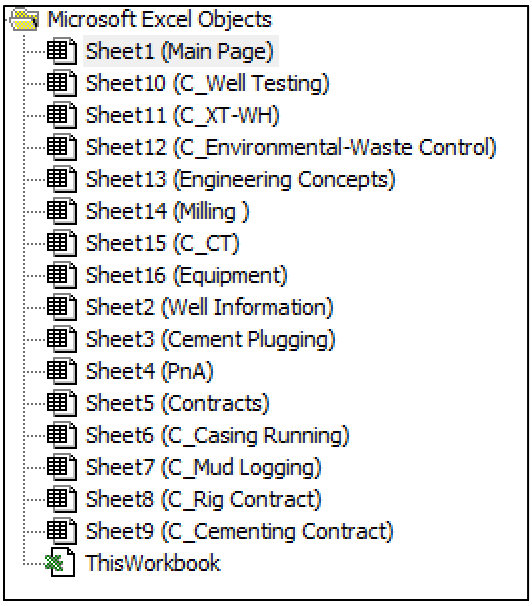


Figure A 6: *Excel File Components*

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